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Research and Development Technical Report

DELET-TR-78-2990-2

III

AD A088450

TACTICAL MINIATURE CRYSTAL OSCILLATOR

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D. L. Harton
D. Brown

THE BENDIX CORPORATION
COMMUNICATIONS DIVISION
East Joppa Road
Baltimore, Maryland 21204

August 1980

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This interim report describes work performed in evaluation of circuits and crystal units for their contribution to oscillator short-term stability performance. Crystals and components were also evaluated for long-term stability. Mechanically, progress is described in material selection, process evolution, and in thermal analysis.

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1. PURPOSE

The objective of this program is the advanced development of the Tactical Miniature Crystal Oscillator (TMXO) having capability for use as a precision frequency/time reference in advanced communications, navigation, and position location systems.

Previous work conducted under Contracts DAAB07-73-C-0199 and DAAB07-75-C-1327 with The Bendix Corporation has demonstrated the feasibility of a lightweight, low power, fast warmup precision quartz reference oscillator based upon a design which employs the vacuum of the TMXO outer enclosure as an insulating medium. In the TMXO, a thermal control circuit acts to maintain the crystal precisely at its upper turn temperature, providing stable frequency operation. Development is to be conducted to optimize TMXO thermal, electrical, and mechanical design and fabrication processes. These procedures will be established and tests conducted to verify TMXO suitability for use over operating conditions and environments encountered in military manpack, vehicular, and airborne usage. Documentation will detail all aspects of TMXO design, process development, special tooling, and performance testing.

Specifically, the major tasks to be performed on this contract are:

Develop both 5.11 MHz and 10 MHz crystal oscillator circuits to provide an acceleration coefficient and short and long term performance consistent with meeting performance characteristics outlined below. A common hybrid microcircuit design shall be evolved permitting either 5.11 MHz (fundamental) or 10 MHz (fundamental or 3rd overtone) operation with only minor modification during assembly. Precision ceramic flatpack crystal units currently in development by ERADCOM are to be employed.

Optimize TMXO electrical design using computer aided design and analysis methods to provide a high yield in circuit performance and reliability at minimum costs. The analysis is to

show that the TMXO final design will meet performance requirements under worst case element value tolerances and parameter variations.

Develop cost effective processes for fabrication of the TMXO hybrid microcircuit assembly and outer enclosure. Emphasis will be placed on obtaining reliable seals of the inner and outer enclosures which will extend the useful life of the TMXO through reduced power aging.

Design and fabricate special fixturing and tooling for assembly, bakeout, vacuum outgassing, sealing and testing of the TMXO.

Establish TMXO test procedures using Quality Conformance Procedures of MIL-O-55310 as a baseline.

Fabricate and test advanced development models of the TMXO incorporating methods and techniques evolved.

The final report is to contain a technical description of all pertinent design and development work accomplished. It will include a complete description of electrical and mechanical components, processes, procedures and fixturing which would permit reproduction of the developed oscillators.

The required characteristics of the TMXO are given below.

Case Outline. The TMXO shall approximate USAECOM outline drawing shown in Figure 1-1.

Weight. The maximum weight shall be 75 grams.

Seal. The TMXO shall be final baked and solder sealed in a vacuum of 1×10^{-6} Torr. Maximum leak rate shall be 1×10^{-12} ATM-cc/sec.

Supply Voltage. 12 V dc $\pm 5\%$.

Warmup Power. 10.0 watts at any ambient temperature.

Operating Power. After warmup maximum power input not to exceed 250 milliwatts at any temperature.

Power Aging. Not to exceed 1% per month.

Nominal Frequency. The nominal frequency of the TMXO shall be 5.115 MHz and 10 MHz.

Voltage Control. The output frequency deviation for a 0 to 10 V dc change applied at the voltage control terminal shall be no less than 2×10^{-7} . The voltage input impedance shall be greater than 10,000 ohms.

Frequency Adjustment. The unit shall be capable of an alternate means of frequency adjustment by termination of the voltage control terminal to ground with a multi-turn 0-100 K ohm potentiometer. The frequency setability shall be better than $\pm 1 \times 10^{-10}$ and tuning range no less than $\pm 1 \times 10^{-8}$ of nominal frequency.

Stabilization Time. Following application of power, the frequency shall be within $\pm 1 \times 10^{-8}$ of final frequency in 3 minutes.

Frequency/Temperature Stability (Steady State). The maximum permissible frequency deviation over the range of -54°C to $+75^{\circ}\text{C}$ shall be $\pm 1 \times 10^{-8}$.

Frequency/Temperature Stability (Transient). The frequency shall not change more than $\pm 1 \times 10^{-8}$ from its initial value when subjected to a positive 10°C amplitude, $1^{\circ}\text{C}/\text{min}$ air temperature ramp starting at -40°C , -5°C , $+30^{\circ}\text{C}$, and $+65^{\circ}\text{C}$.

Frequency/Acceleration Stability. The maximum frequency change measured during static acceleration shall be 1×10^{-9} when tested in accordance with Method 513, Procedure II (helicopter category) MIL-STD-810B. Permanent frequency change shall be no greater than $\pm 1 \times 10^{-9}$.

Frequency/Vibration Stability. The maximum permissible average frequency change measured during and following vibration without isolators shall be $\pm 1.0 \times 10^{-9}$ when tested in accordance with Method 514, Curve M, MIL-STD-810B. The frequency deviation represented by the modulation side bands at the vibration frequency shall not exceed 1×10^{-9} times the peak acceleration level specified for that frequency by curve M.

Frequency/Shock Stability. The maximum permissible frequency change following a shock of 50g. 11 msec shall be $\pm 1 \times 10^{-9}$ when tested in accordance with Method 213, Condition G, MIL-STD-202D.

Frequency/Attitude Stability. The maximum frequency change for a $90 \pm 5^{\circ}$ attitude change in any axis shall be 1×10^{-9} .

Frequency/Altitude Stability. The maximum frequency change following an altitude change from sea level to 10,000 ft shall be $\pm 1 \times 10^{-9}$.

Frequency/Load Stability. The maximum frequency deviation for a load variation of 1000 ohm $\pm 10\%$, 20° phase shall be $\pm 1 \times 10^{-9}$.

Frequency Voltage Stability. The maximum permissible frequency deviation for a supply voltage variation of 12 volts $\pm 5\%$ shall be $\pm 1 \times 10^{-9}$.

Frequency Aging. Aging of the output frequency shall not exceed 2×10^{-10} per week, operating, after a 30 day stabilization period.

Short Term Stability. The maximum rms frequency deviation shall be $\pm 1 \times 10^{-11}$ for averaging times ranging from 1 sec to 20 minutes under conditions of input voltage and ambient temperature controlled to ± 1 mV and $\pm 0.1^\circ\text{C}$ respectively.

Frequency Recovery at -40°C Ambient. The output frequency after warmup during each turn-on period for a 5 cycle frequency recovery shall remain within $\pm 3 \times 10^{-9}$ of the frequency measured on the first cycle. Each cycle shall consist of complete frequency stabilization during turn-on, followed by complete thermal stabilization after power is removed.

Output Voltage. A minimum of 0.170 rms at the output frequency shall be available across an external resistive load of 1 K ohms. The output waveform shall be a sine wave.

Ambient Temperature Range. The TMXO shall meet all requirements of this specification over the ambient temperature range of -54° to $+75^\circ\text{C}$.

Microcircuit Design and Construction. Microcircuit design and construction shall be in accordance with para 3.5 of MIL-M-38510. Exception for use of epoxies for non-electrical connection shall be requested in writing to the contracting office stating type, company experience and inspection and in process controls to be employed.

Quartz Crystal. Ceramic flatpack, microcircuit compatible quartz crystal units in accordance with MIL-C-3098.

Screening. The TMXO microcircuit sub-assembly shall be capable of meeting screening requirements of Method 5008, MIL-STD-883 with the following exceptions:

- a. Bond Strength (para. 3.2.2.1) shall be performed on all units.
- b. Temperature Cycling (para. 3.2.3.4) shall be performed in accordance with test condition B.
- c. Mechanical Shock or Constant Acceleration (para. 3.2.3.5). Constant acceleration only shall be performed.
- d. Omit test procedure 3.2.1.1, 3.2.3.11, 3.2.3.12, and 3.2.3.13.

Metric Dimensioning. Metric dimensioning shall be employed.

Nuclear Survivability. Consideration shall be given to the selection and development of parts, materials, processes, design details, and operating principles to insure realization of the inherent level of nuclear and EMP hardness of which the circuit/sub-system is capable. Typical radiation levels of interest fall in the ranges: 10^2 - 10^5 roentgen (cobalt 60) and 10^{12} - 10^{14} neutrons/cm² (1 MeV equivalent). Test and/or analysis of the design shall be made to indicate the most probable modes of degradation or malfunction and to provide a first order estimate of the degrees of nuclear hardness achieved.

2. ACCOMPLISHMENTS

Planned activities were accomplished during this reporting period, as described below.

2.A ELECTRONICS DESIGN

At the beginning of the second six month performance period, the status of the electronic design was as follows: Preliminary measurements had indicated unsatisfactory performance in the area of short term stability. Test oscillators, operating with the developmental ceramic flat pack crystals available at the time, exhibited erratic behavior. Data recorded over a period of time would show intervals of relatively stable performance punctuated by periods of serious perturbations. The causes of the degradation could reside in environmental effects, oscillator-contributed perturbations, or from defects within the crystals themselves. When other crystals of known quality were substituted in the test oscillators, the performance was good; however, it could be argued that, since the substitute crystals (third or fifth overtone units) had smaller motional capacity, they would necessarily be more resistant to perturbations of termination impedance presented by the oscillators.

Until these questions could be resolved, progress in circuit design, and further crystal and component evaluation was limited. The approach taken was to attempt to isolate the source of the perturbations, by measuring, independent of test oscillators, the low frequency phase perturbation associated with circuit elements and components, including crystals.

(1) PHASE PERTURBATION MEASUREMENT. An implementation of a facility for these measurements is shown in Figure 2-1.

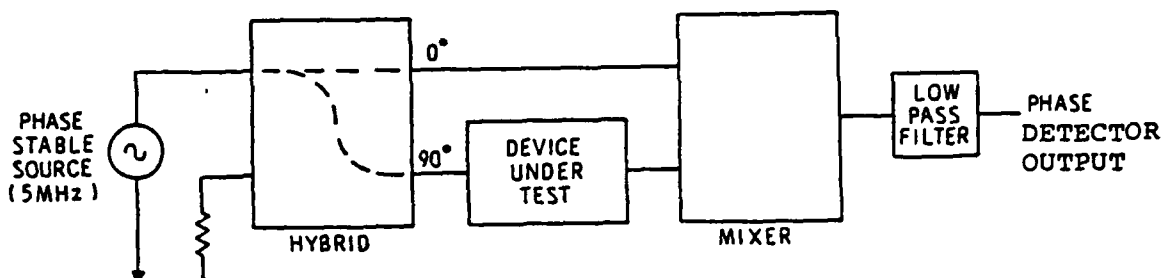


FIGURE 2-1 PHASE PERTURBATION MEASUREMENT FACILITY

A highly phase-stable source is divided into direct and quadrature components by a 90 degree hybrid. The device under evaluation (crystal, amplifier, etc.) is inserted into one path. The length of the other path is selected to present quadrature inputs to the mixer, with the direct component of the mixer output representing the differential phase. The amplitude of this component represents the phase perturbations introduced by the device under evaluation.

The operating signal level provides a gradient of the order of 1 volt/radian, or 1 μ volt per micro-radian. The phase analog signal is fed to a low noise amplifier contributing <1 μ volt peak to peak (P.P) over periods from 1 second to 1 minute. The phase stability implied by the oscillator specification of frequency stability is as follows: a short term stability of $\Delta f/f = 1 \times 10^{-11}$ @ $f = 5$ MHz requires $\Delta f(\text{RMS}) < 50 \times 10^{-6}$ Hz. With $\pi/2$ radians phase change over a 10 Hz crystal 3 dB bandwidth, $\Delta f/\Delta\phi = 6.4$ Hz/radian, resulting in phase perturbations

$$\Delta\phi < \frac{50 \times 10^{-6}}{6.4} = 8 \mu \text{ radians RMS}$$

The phase perturbation resolution of the facility is therefore about an order of magnitude better than the specification limit.

When crystals are to be evaluated for phase perturbation contribution, the facility is configured as shown in Figure 2-2. Matching elements C_1 and C_2 and attenuators are chosen to isolate the crystal while introducing losses into the crystal circuit comparable to the effective resistance of the crystal itself, to maintain circuit $Q = 1/2 Q_{XTAL}$. The signal level provides crystal current about 0.5 ma. The amplifier following the crystal circuit has previously been shown to introduce no appreciable phase perturbation. The attenuators, crystal/matching network and amplifier are installed within a proportional controlled oven having short-term temperature variations < 1 millidegree. The crystal is operated close to its turn temperature.

In order to accommodate various crystals without requiring tuning of the matching components, an adjustable frequency source has been configured as shown. The synthesizer signal, when divided by 100 shows stability comparable to the 5 MHz stable source (a few parts in 10^{12} over 10 seconds). The 5.115 MHz bandpass filter provides > 35 dB rejection of the undesired mixer product. The filter phase slope is approximately 50μ radians per cycle so that the filter must be carefully constructed to avoid introducing phase perturbations. Prior to an evaluation of one of the developmental ceramic flat pack crystals, as a calibration, a 5.115 MHz third overtone (Hewlett Packard) crystal of known quality was installed, and measurements of phase detector output in microvolts were made at 2 second intervals. Runs of 1280 data points were taken (approximately 42 minutes per run) and the RMS deviation computed for the 2 second intervals, as well as deviations of 20 second averages. To determine possible contributions of amplifier A3, the isolation between the crystal and the amplifier was increased 12 dB by increasing attenuator A2 by 6 dB, and the RMS deviations remeasured. Runs taken with and without the additional attenuation were interleaved, to verify repeatability, and to detect changes in performance of the test facility.

Based on measured frequency to phase dependence, the equivalent frequency deviations for this crystal were:

	2 Second Δf_{RMS}	20 Second Δf_{RMS}
With $A_2 = 6$ dB	20.4 μHz	37.5 μHz
With $A_2 = 0$ dB	20.7 μHz	38.5 μHz

The data indicates that there is no appreciable contribution to phase perturbation due to the amplifier, since the 12 dB reduction in isolation caused $\ll 1$ dB increased perturbation amplitude. The resulting fractional frequency stability would be

$\frac{\Delta f}{f}(2 \text{ Sec}) = 4 \times 10^{-12}$ and $\frac{\Delta f}{f}(20 \text{ Sec}) = 7.5 \times 10^{-12}$, consistent with measured performance of the crystal in its oscillator.

The perturbation introduced by fundamental crystal CR 90 was then measured. Crystal CR 90 had shown short term stability comparable to the best of the fundamental crystals available at the time in the test oscillators. Data runs for this crystal exhibited great variance among runs, and indicated large perturbations. Averages for several runs for the fundamental crystal were:

	2 Second Δf_{RMS}	20 Second f_{RMS}
With $A_2 = 6$ dB	318 μHz	268 μHz
With $A_2 = 0$ dB	425 μHz	245 μHz

The 2 second interval data average indicates ≈ 2.5 dB less perturbation amplitude with the 12 dB increased isolation from the amplifier; however, a similar trend is missing in the 20 second average. We therefore conclude that, for the fundamental crystal, the principal source of phase perturbation is not the result of parametric changes at the amplifier input reflecting changes into the crystal circuit. Since the amplitude of the phase detector output with the Hewlett Packard crystal is an order of magnitude below that observed with the fundamental crystal, the

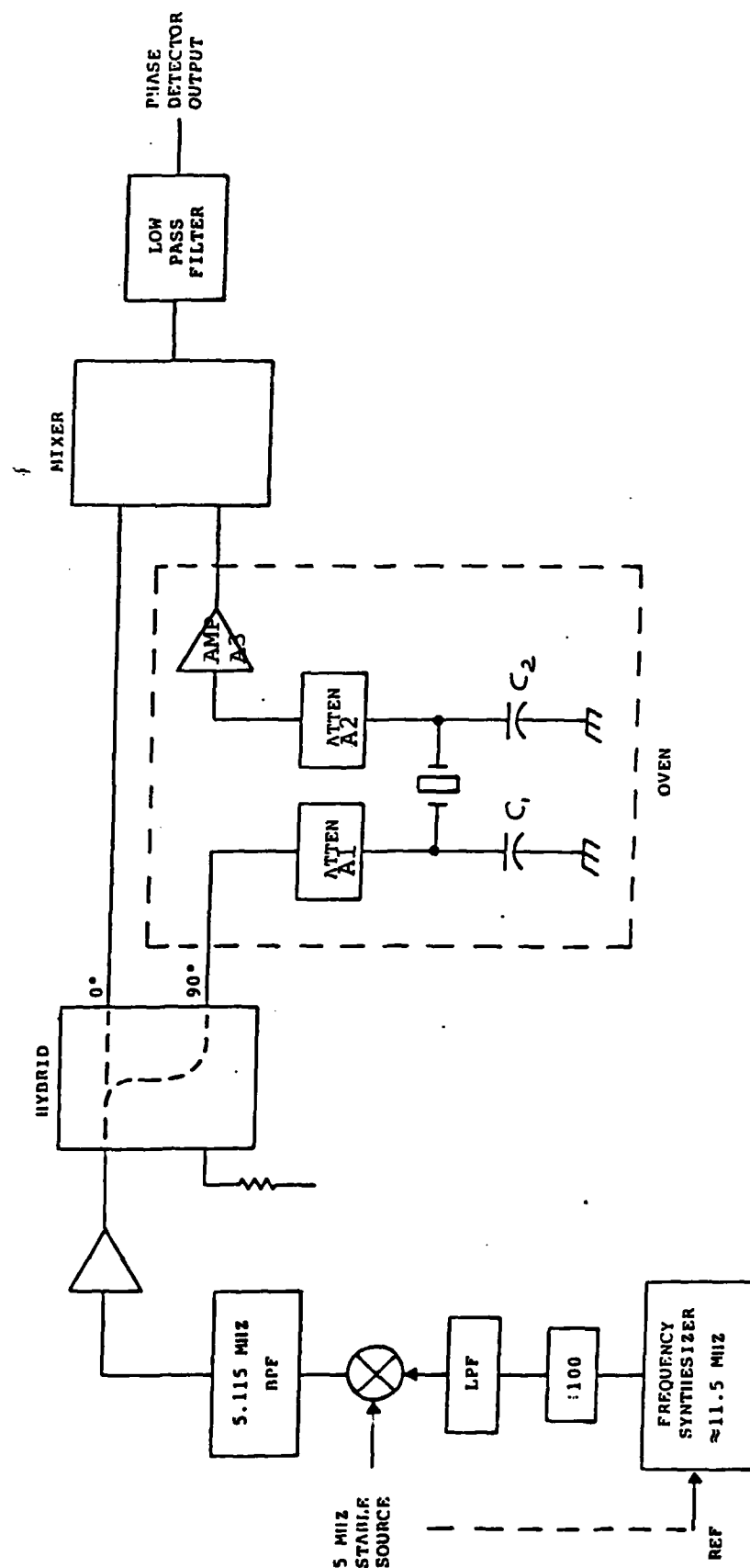


FIGURE 2-2. CRYSTAL PHASE PERTURBATION TEST FACILITY

contribution of any phase instability of the excitation signal to the phase perturbation measurement of the fundamental crystal must be small. As a result we conclude that the major contributor to the measured phase perturbations is the particular fundamental crystal itself.

(2) SHORT TERM STABILITY EVALUATION OF FUNDAMENTAL 5.115 MHZ CRYSTALS. Shortly after completion of the phase perturbation measurements of crystal CR 90, crystal CR 186 was received and installed in the test oscillator shown in Figure 2-3. The short term stability, as observed on the chart recorder (see Figure 2-4) appeared to be considerably better than any other observed to date with fundamental crystals, and approached the stability previously observed with the Bliley third overtone crystal shown in Figure 2-5. Crystal CR 186 was subsequently operated in the "no reactance" circuit shown in Figure 2-6. The results are shown in Figure 2-7 with similar short term stability performance observed.

Figure 2-8 illustrates the Allan variance measurements of CR 186 in the two test oscillators, compared to measured performance of the H.P. 10544A oscillator. The crystal from this oscillator has been used as a comparison standard in the phase perturbation tests. Figure 2-8 also shows the fractional frequency stability of a test signal derived from a Frequency Synthesizer at 11.5 MHz by division of 100 times, related to the 5.115 MHz test frequency, as an indication of the residuals in the amplifier/counter portion of the test setup.

The availability of a fundamental crystal with the short term stability performance of CR 186 simplified succeeding tasks in a number of areas:

- 1) Individual test oscillators were qualified for use in evaluating short term stability of other crystals, which is a much simpler procedure than the phase perturbation method.
- 2) Improved short term stability allowed determination of longer term aging of other components more quickly.

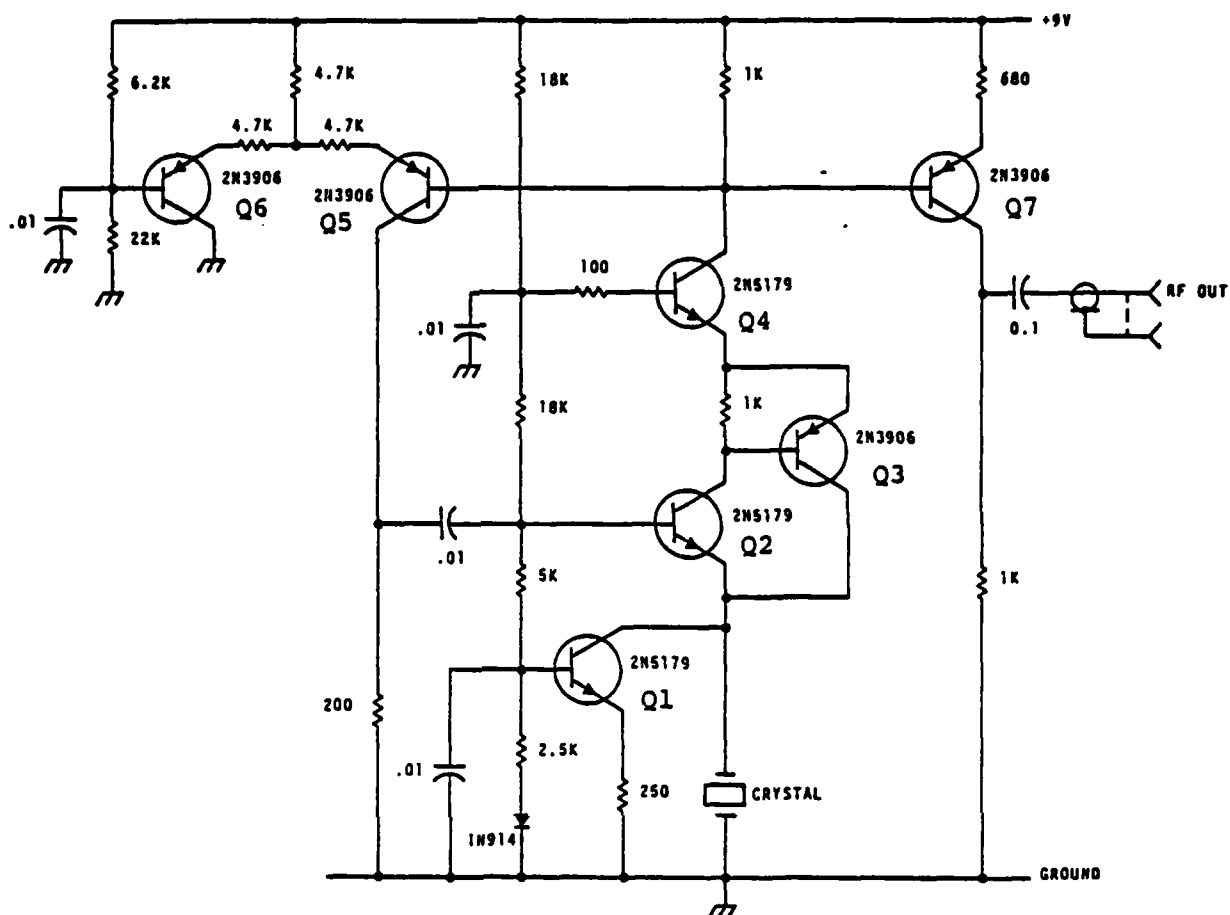


FIGURE 2-3 SELF-LIMITING TEST OSCILLATOR SCHEMATIC

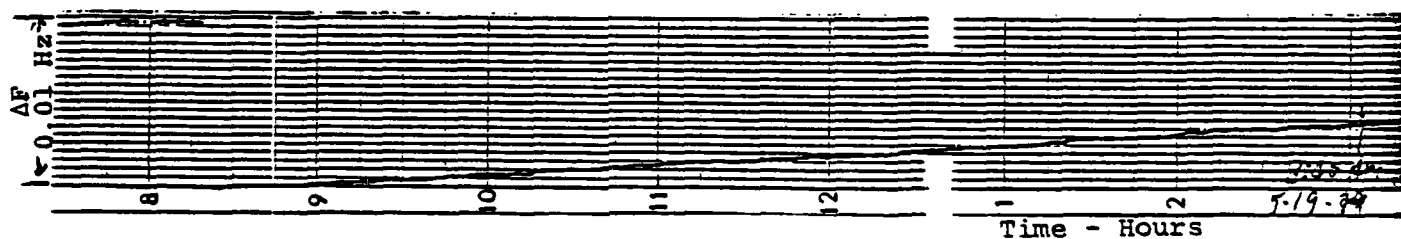


FIGURE 2-4 CRYSTAL CR 186 STABILITY PERFORMANCE

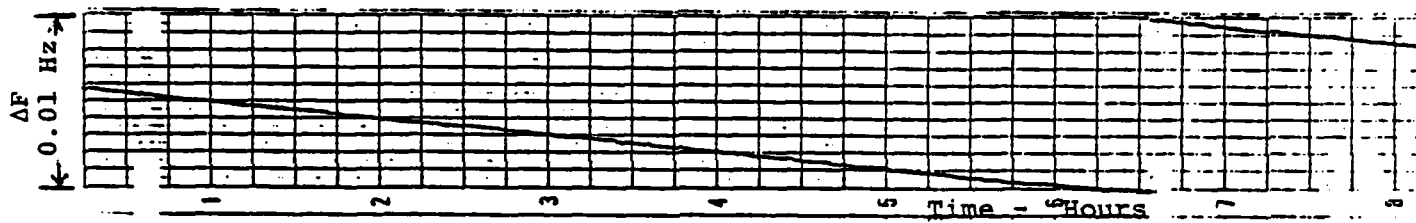


FIGURE 2-5 BLILEY THIRD OVERTONE STABILITY PERFORMANCE

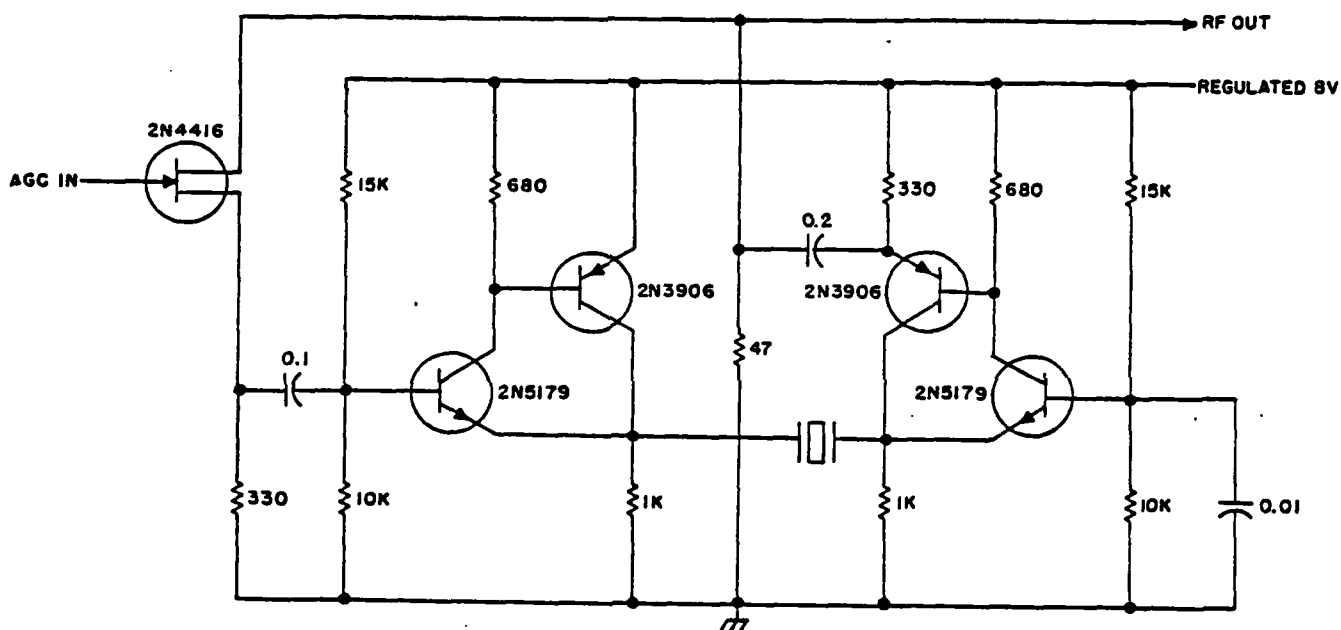


FIGURE 2-6 "NO REACTANCE" TEST OSCILLATOR SCHEMATIC

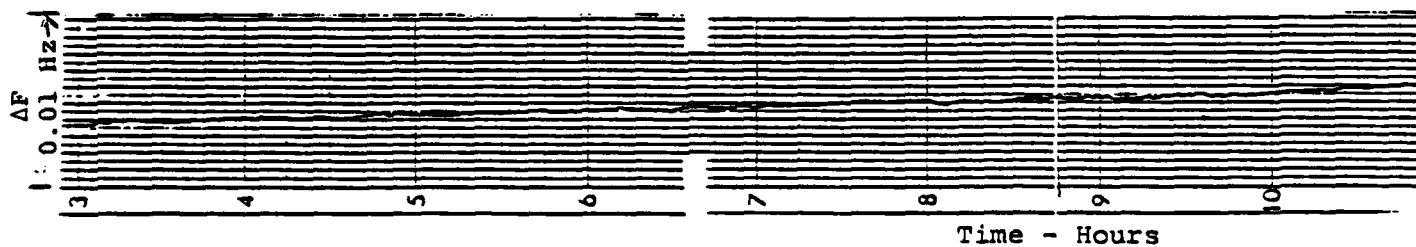


FIGURE 2-7 CRYSTAL CR 186 STABILITY PERFORMANCE

K&E SEMI-LOGARITHMIC 46 6463
7 CYCLES X 60 DIVISIONS
MADE IN U.S.A.
KEUFFEL & ESSER CO.

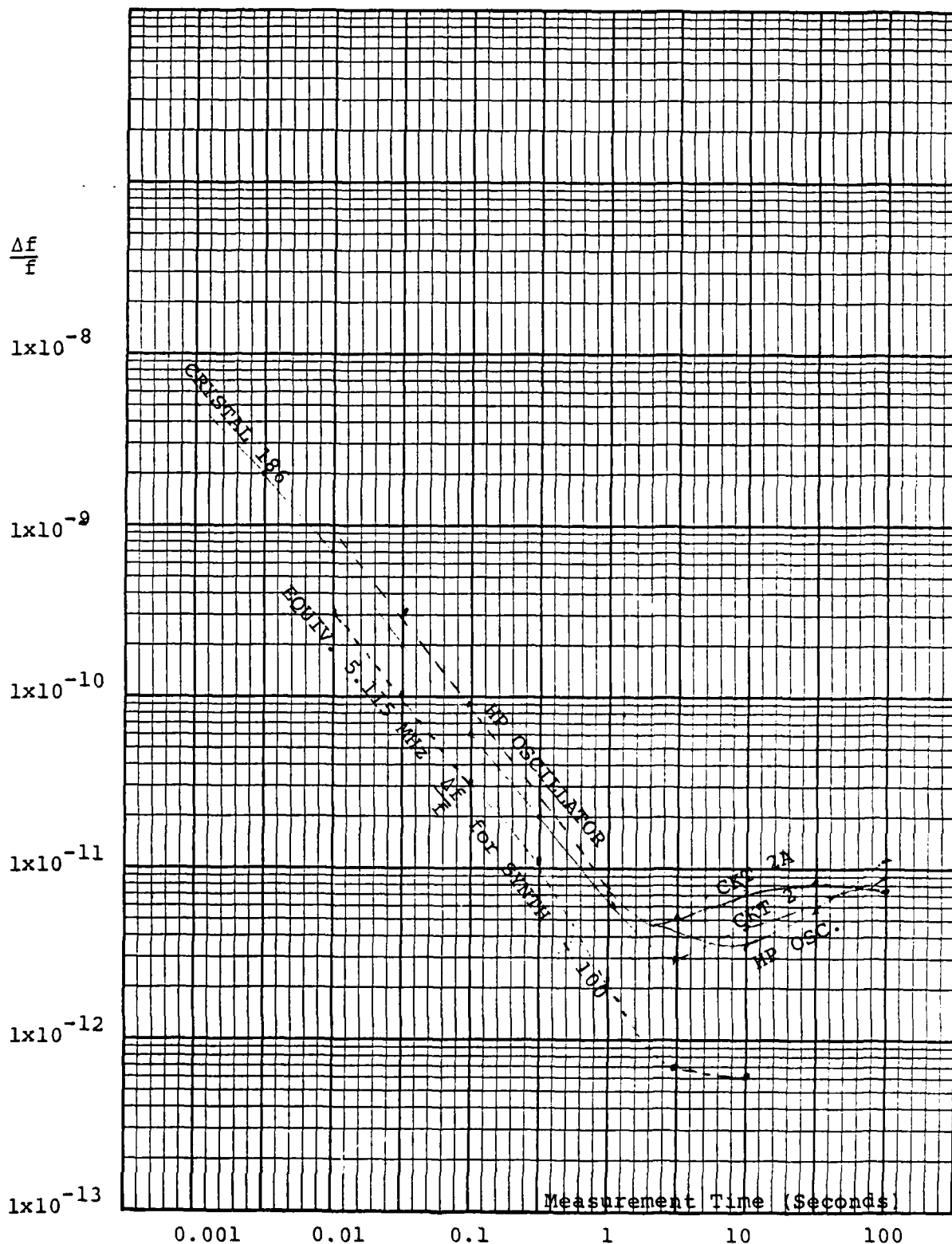


FIGURE 2-8 ALLAN VARIANCE COMPARISON

- 3) Oscillator frequency responses to small temperature excursions were determined thereby facilitating the development of the TMXO temperature control circuits.

The highest priority item was considered to be the evaluation of the short term stability performance of the developmental crystals* being produced at General Electric Neutron Devices (G.E.N.D.), and to demonstrate conclusively that the variations of crystal/oscillator performance experienced were crystal related. The following test sequence was therefore carried out.

1. Place the best, most consistent crystal (CR 186) in the oscillator circuit of Figure 2-7/test oven and monitor the unit for 24 hours.
2. Place another crystal, previously identified to be noiser, in the same test oven and circuit and monitor for 24 hours.
3. If irregularities or unpredictable behavior become evident, immediately replace the test crystal with the known, previously demonstrated in step 1, good crystal and observe the behavior. If the irregularities or unpredictable behavior is eliminated, it can be safely concluded that the problem is crystal related. If not, it can be safely concluded that some other source or disturbance is the cause.
4. This test will be conducted alternating the known "good" crystal and suspected crystals until a conclusion is reached. (i.e., problems being classified as "crystal related" or non-crystal related.")

Precautions were taken to monitor and/or limit the effects of many of the known disturbances, such as:

1. Temperature of the oscillator/crystal system is monitored and recorded with a resolution of $\pm .002^{\circ}\text{C}$.

*All ceramic flatpack enclosed crystal units evaluated in this program were experimental devices produced during the early phases of the TMXO crystal development program at GEND. Due to the limited numbers available, all units made at GEND were submitted, unscreened, except for leak rates. Reported performance deficiencies, thus, must not be interpreted as being intrinsic to the ceramic flatpack crystal design.

2. Primary line power is monitored to all power supplies and test equipment with a Dranetz Power Line Disturbance Meter Series 606.

3. All measurements are taken inside a screen room.

Figure 2-9 shows the configuration of the evaluation facility.

The demonstration was accomplished by plotting performance of the known good crystal (CR 186) under controlled conditions to be used as a reference plot. Other crystals were then introduced into the facility for comparison, with the good crystal reintroduced between candidate crystals to demonstrate confidence in the measurement technique and environment. The results are reproduced in Figure 2-10(1), 2-10(2), and 2-10(3), and show that the performance of the facility with crystal CR 186 was consistent throughout the period, while performance with the other crystals showed various degrees of degradation.

As a result of these tests, the decision was made to furnish G.E.N.D. with an oscillator/oven assembly, to allow G.E.N.D. to perform crystal performance evaluation at their facility prior to delivery of further crystals to Bendix. Oven #4 was selected and updated to be, to the extent possible, the twin of the oven used at Bendix for crystal evaluation. A 100 pf capacitor was included in series with the crystal in both. Oven #4 was operated for several days with crystal CR 186 to demonstrate performance comparable with the measurements described above. Representative data is shown in Figure 2-11. Crystal CR 186 was then removed, and crystal CR 192 was installed, and the assembly shipped to G.E.N.D. on 20 June 1979, together with maintenance documentation and temperature control calibration data.

Subsequently, short term stability testing at Bendix was completed on twenty-seven fundamental 5.115 MHz crystals. Crystal status is shown in Table 2-1. Crystal CR 232 had high series resistance and would not operate in the test oscillator.

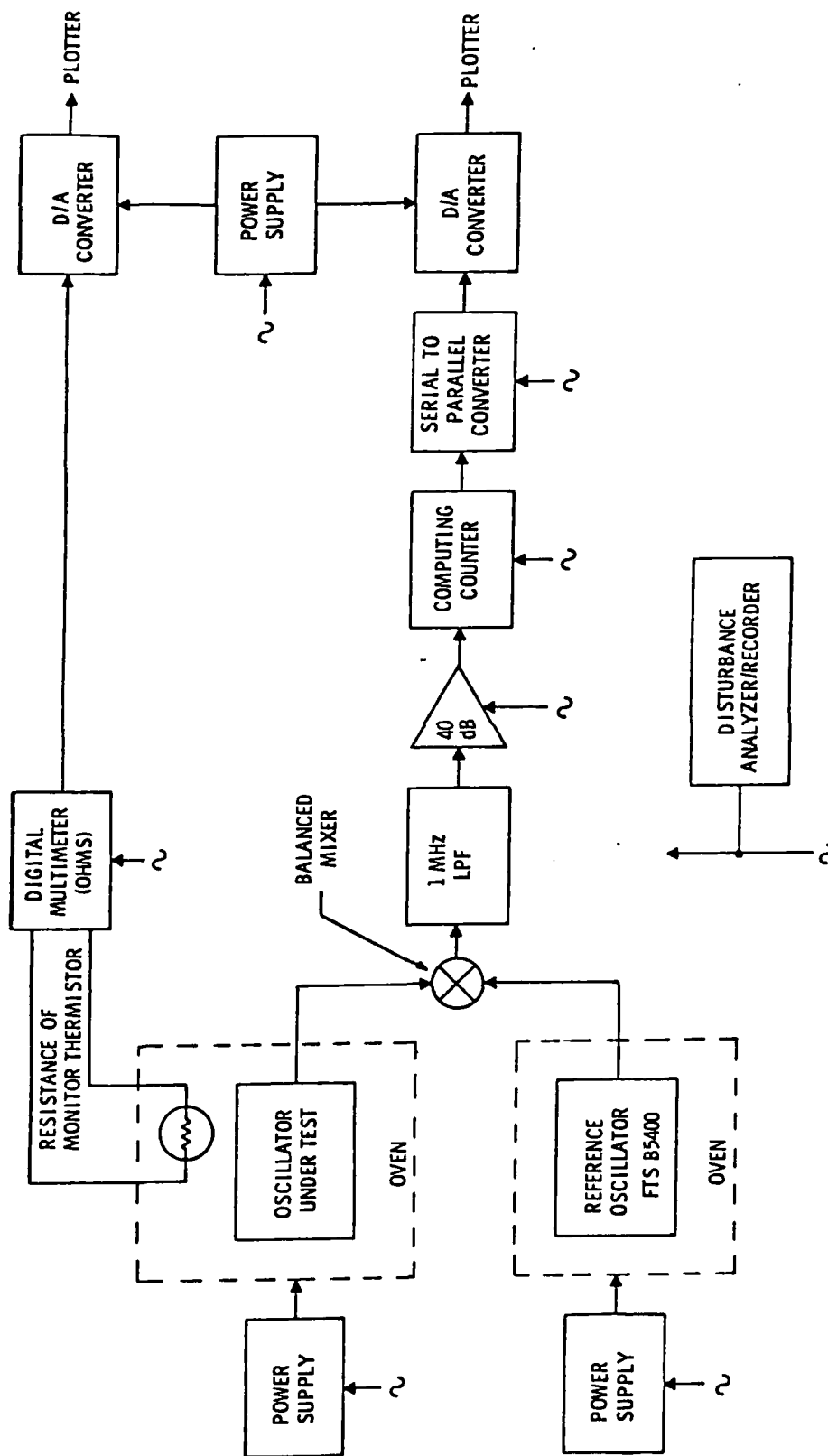
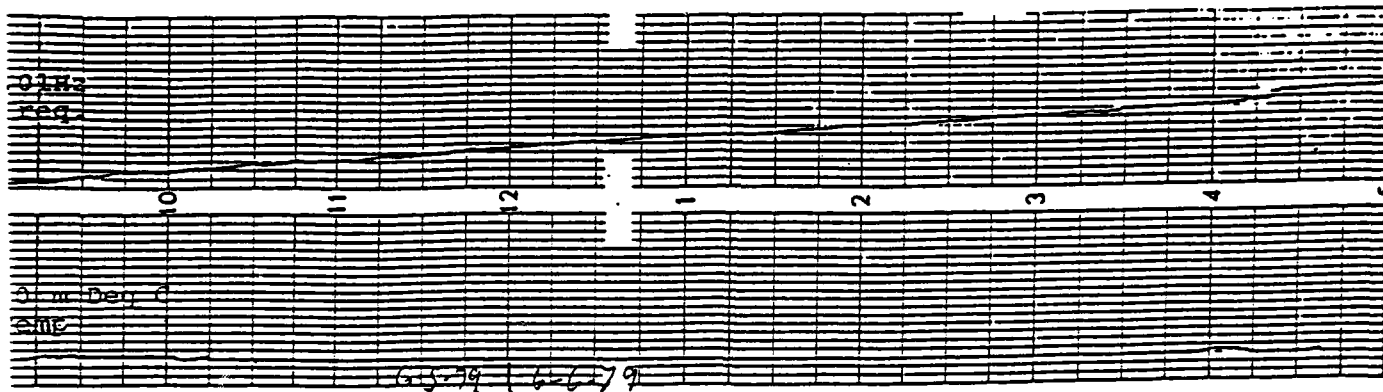
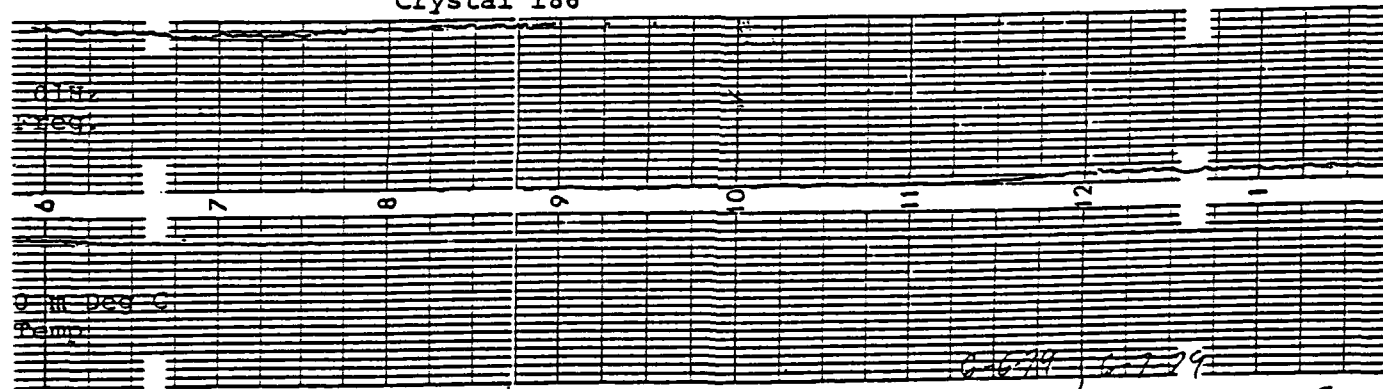


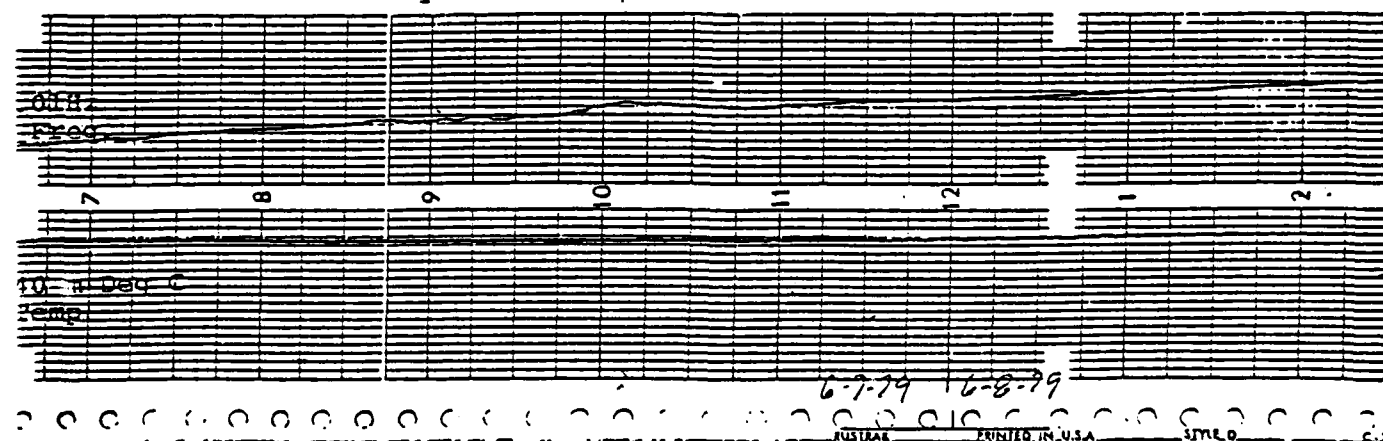
FIGURE 2-9 CRYSTAL/OSCILLATOR EVALUATION FACILITY



Crystal 186

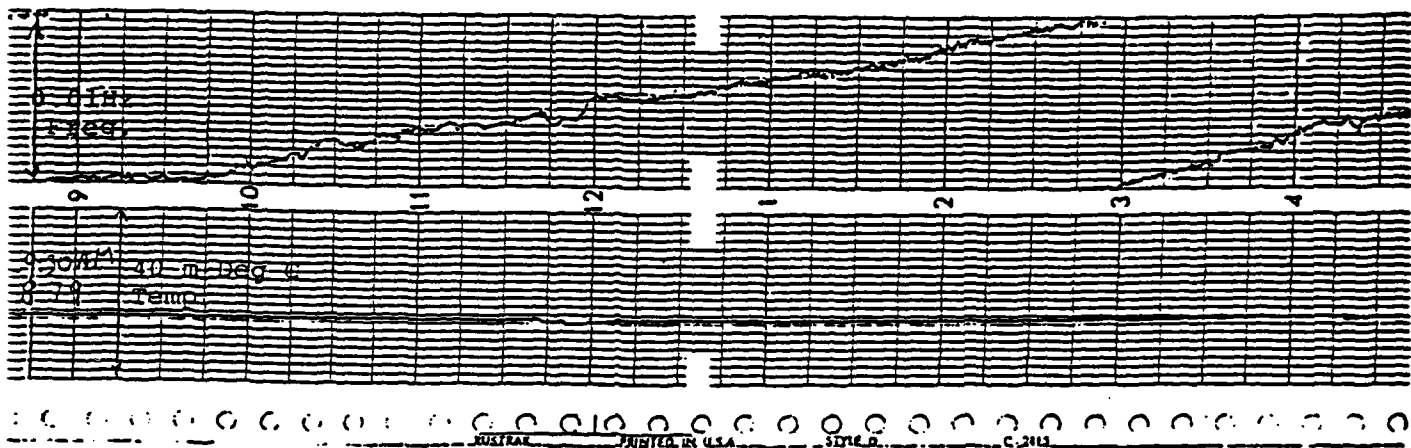


Crystal 197

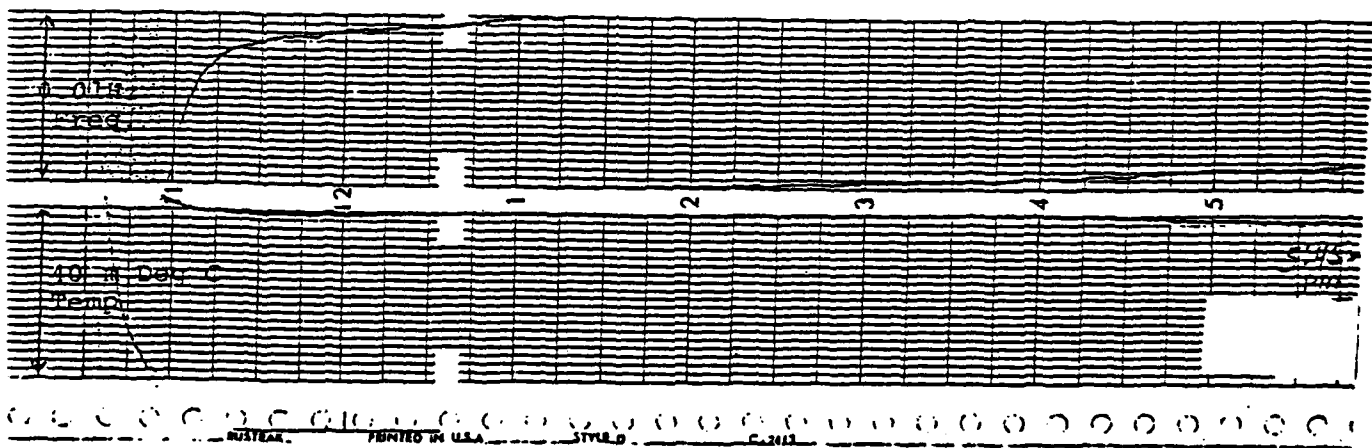


Crystal 186

Figure 2-10(1)

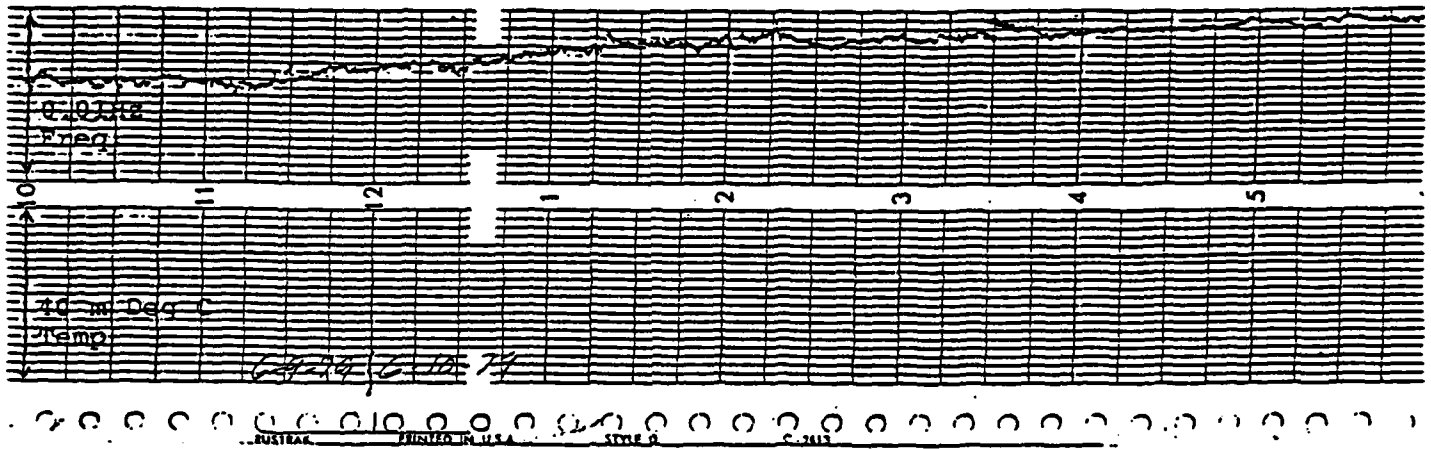


Crystal 192

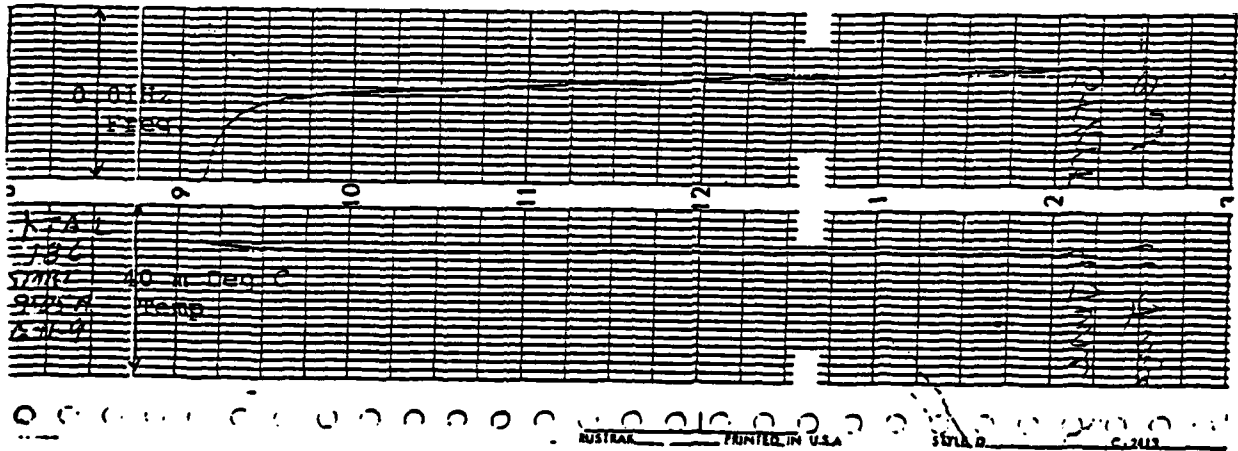


Crystal 186

Figure 2-10(2)

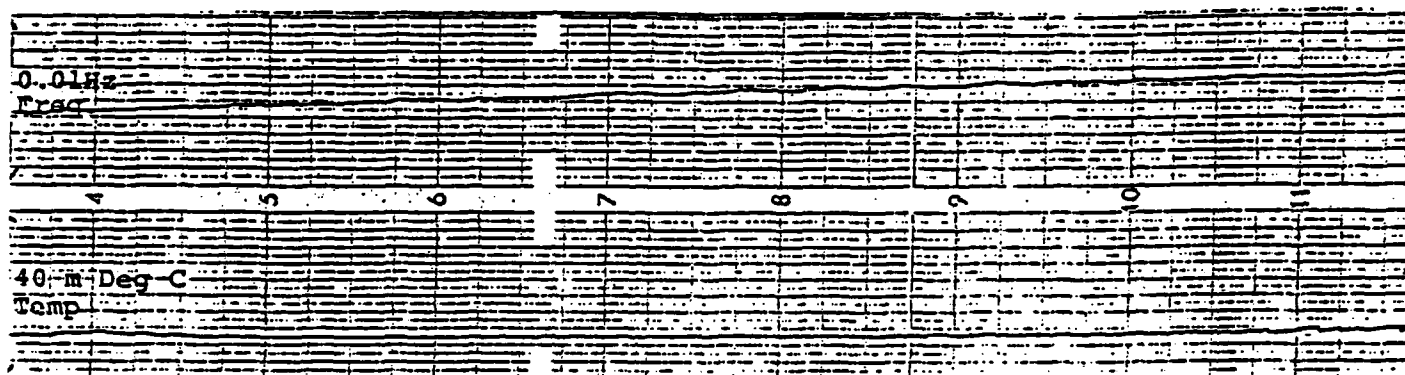


Crystal 194

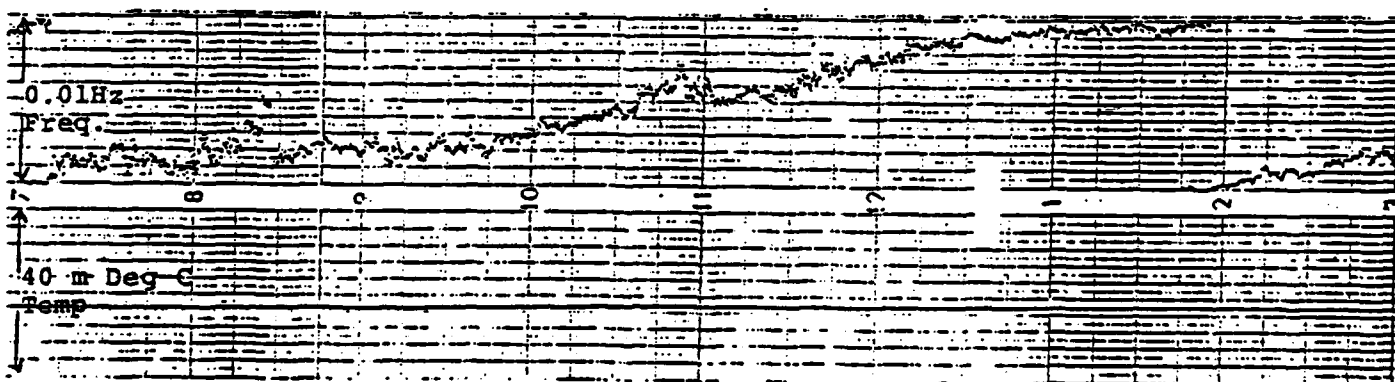


Crystal 186

Figure 2-10(3)



Oven 4 with Crystal 186



Oven 4 with Crystal 192

Figure 2-11

Table 2-1

Crystal Status (1 August 1979)

Crystal S/N	Frequency MHz	Date Received	Short Term Stability	Comments
186	5.115	5/10/79	Good	Resonator Flow Sheet Missing
192	↑	5/24/79	Poor	Returned to G.E.N.D. 6/19/79
194		5/24/79	Poor	
195		7/2/79	Poor	Resonator Flow Sheet Missing
197		5/24/79	Fair	
203		7/2/79	Poor	Resonator Flow Sheet Missing
205		7/2/79	Poor	Resonator Flow Sheet Missing
208		6/12/79	Fair	Resonator Flow Sheet Missing
209		6/12/79	Fair	Resonator Flow Sheet Missing
211		6/1/79	Poor	
212		6/1/79	Good	
213		6/7/79	Fair	
217		6/7/79	Poor	
218		6/7/79	Poor	
220		6/7/79	Poor	
221		6/7/79	Poor	
223		6/7/79	Poor	
225		6/7/79	Poor	
226		6/7/79	Fair	
227		6/7/79	Poor	
228		6/7/79	Poor	
232		7/23/79	--	Does not oscillate
233		7/23/79	Poor	
234		7/23/79	Poor	
235		7/23/79	Poor	
236		7/23/79	Poor	
238	↓	7/23/79	Poor	
240	5.115	7/23/79	Poor	

Representative segments of the stability records are shown in Figures 2-12 through 2-20. Note that the frequency record sensitivity is $\frac{\Delta f}{f} = 2 \times 10^{-9}$ full scale, and that the amplitude represented by the smallest division (1/20 full scale) is $\frac{\Delta f}{f} = 1 \times 10^{-10}$. The specification limit of $\frac{\Delta f}{f} < 1 \times 10^{-11}$ RMS over 20 minutes therefore implies less than one small division peak to peak variation over 20 minutes. The horizontal (time scale) graduations represent 15 minute intervals.

Only two crystals (CR 186 and CR 212) appear to be within the TMXO specification limit. Possibly five more crystals are categorized as fair, while the remaining twenty, including most units received on 6/7/79 and after are considered to have poor stability performance.

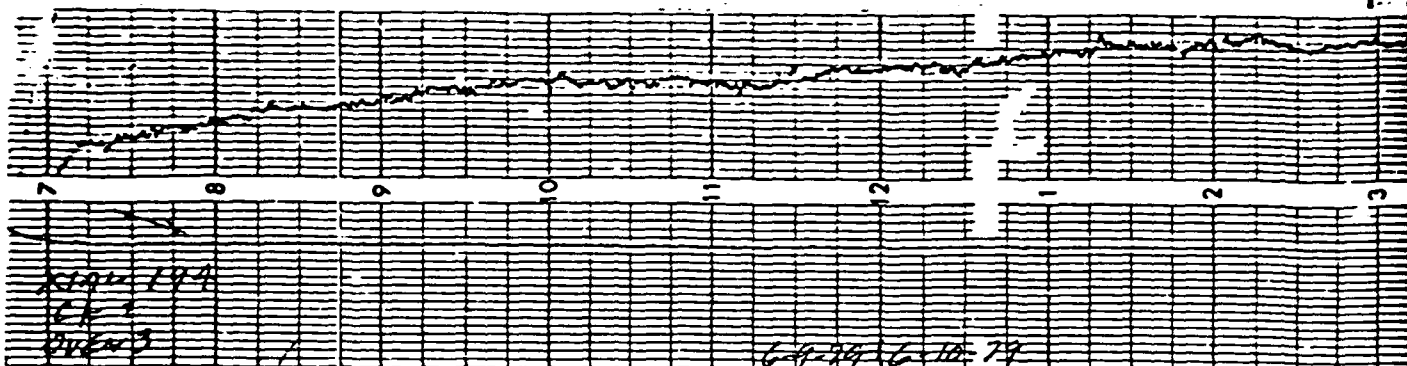
The purpose of the evaluation was to select the best crystal units for the oscillator construction, and to assist the design activity in correlating fabrication/processing events with crystal unit performance. (See footnote on page 16.)

(3) BLILEY FUNDAMENTAL CRYSTAL EVALUATION. In order to demonstrate that fundamental crystals can provide short term stabilities comparable to high quality overtone devices, a fundamental 5 MHz unit was procured from the Bliley Electric Company, fabricated using the same processing techniques as their BG5LAS-55/35 devices. The parameters of the crystal are:

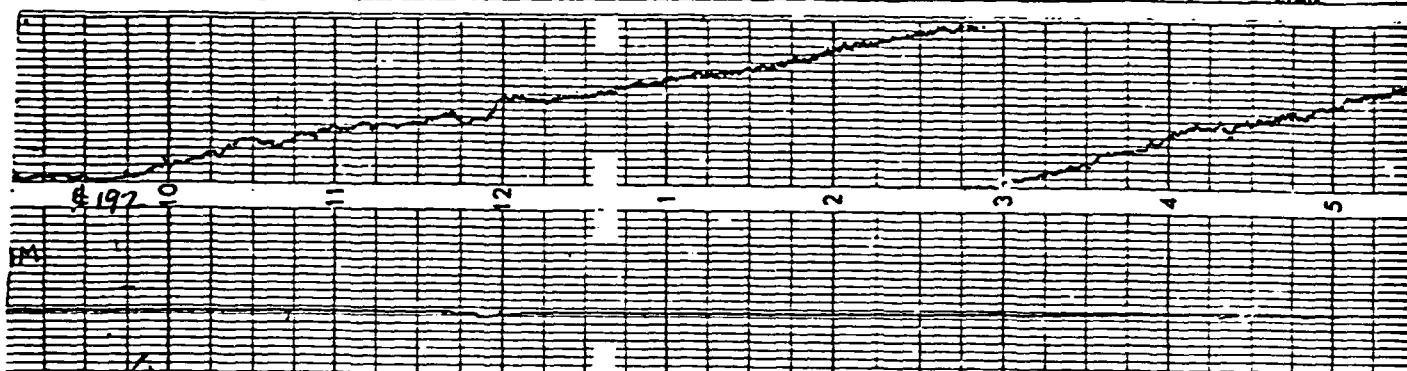
$$\begin{aligned}C_1 &= 0.009 \text{ pf} \\r_s &= 2 \text{ ohms} \\Q &= 1.75 \times 10^6\end{aligned}$$

The unit was operated in our "no reactance" test oscillator (Figure 2-6) at 0.5 ma crystal current and produced the following short term stability data. (The FTS B5400 oscillator was used as the reference standard).

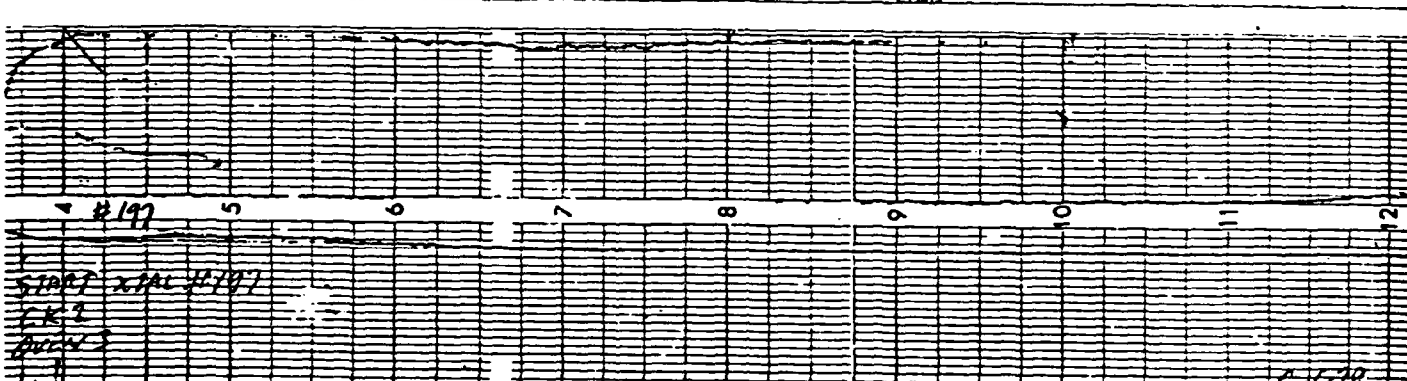
Measurement Time	$\frac{\Delta f}{f}$
0.1 Sec	2.9×10^{-11}
0.3 Sec	1.0×10^{-11}
1.0 Sec	3.6×10^{-12}
3.0 Sec	1.2×10^{-12}
10. Sec	1.0×10^{-12}



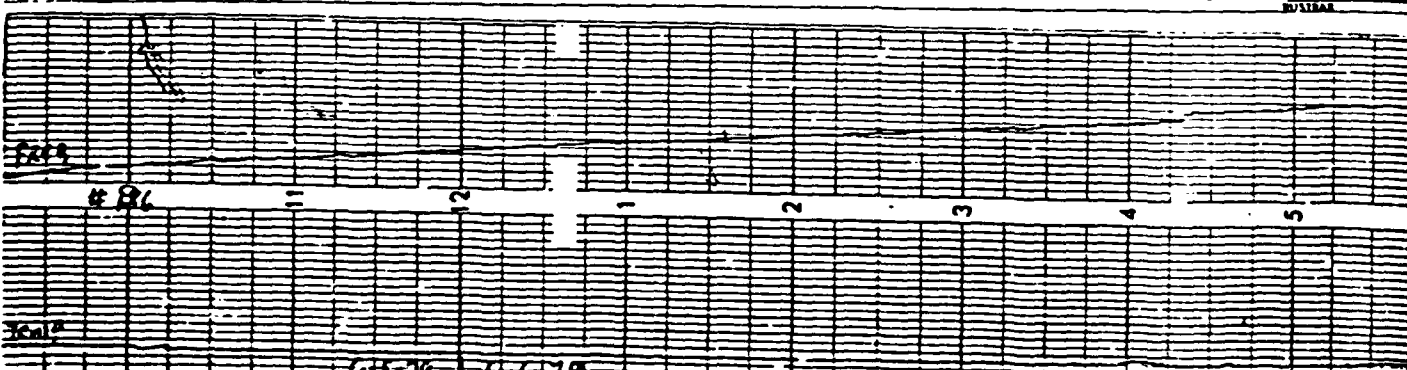
Crystal #1



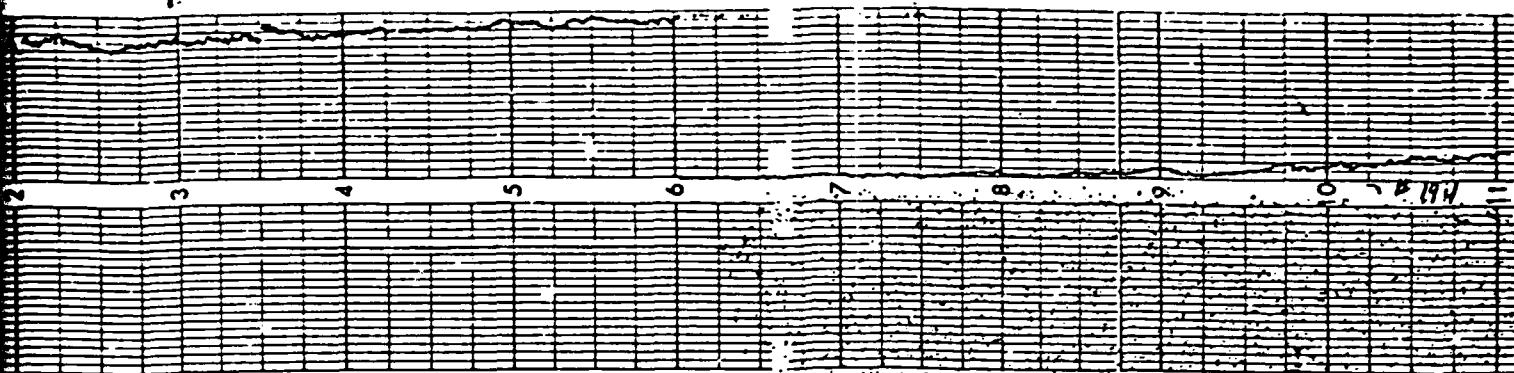
Crystal #2



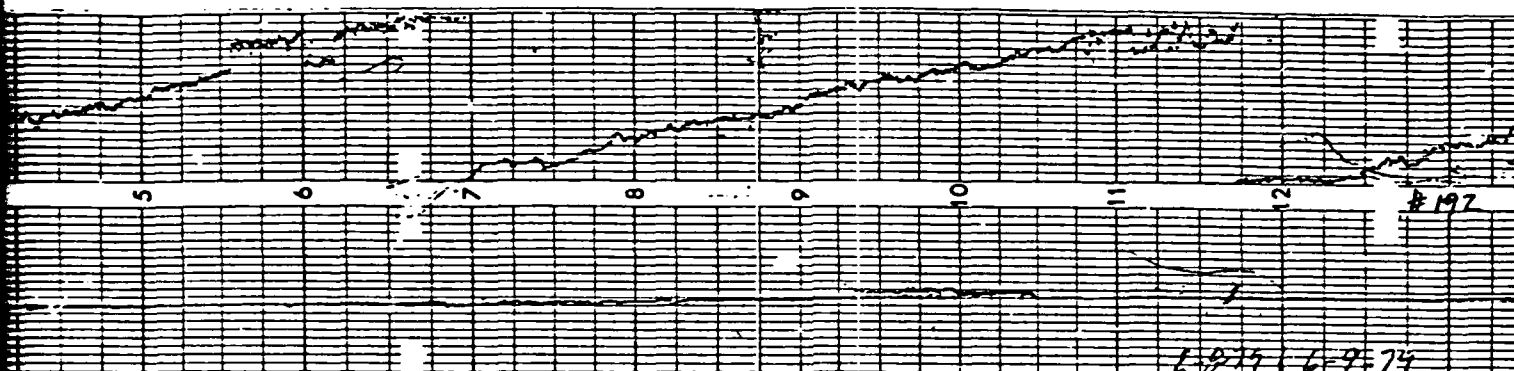
Crystal #3



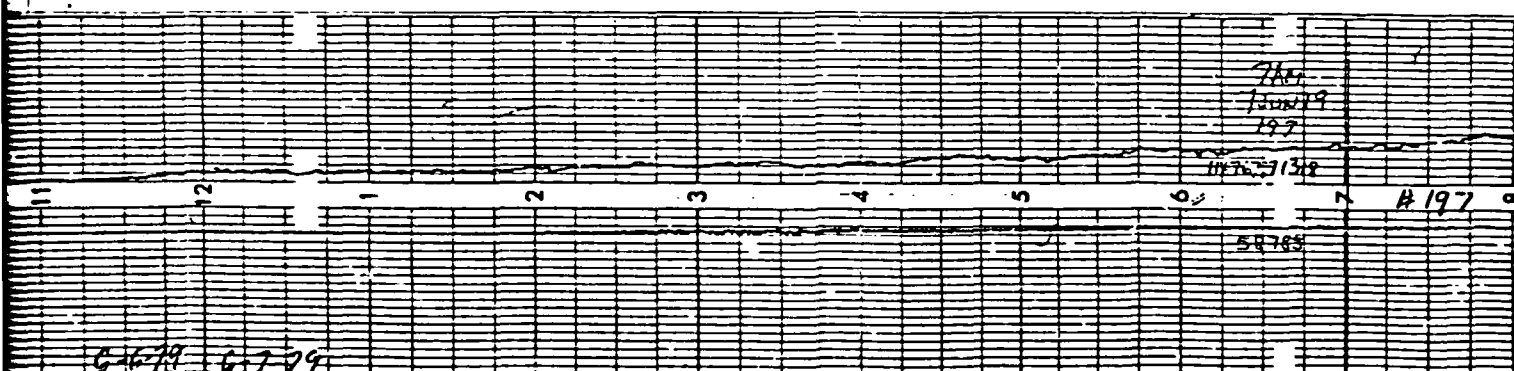
Crystal #4



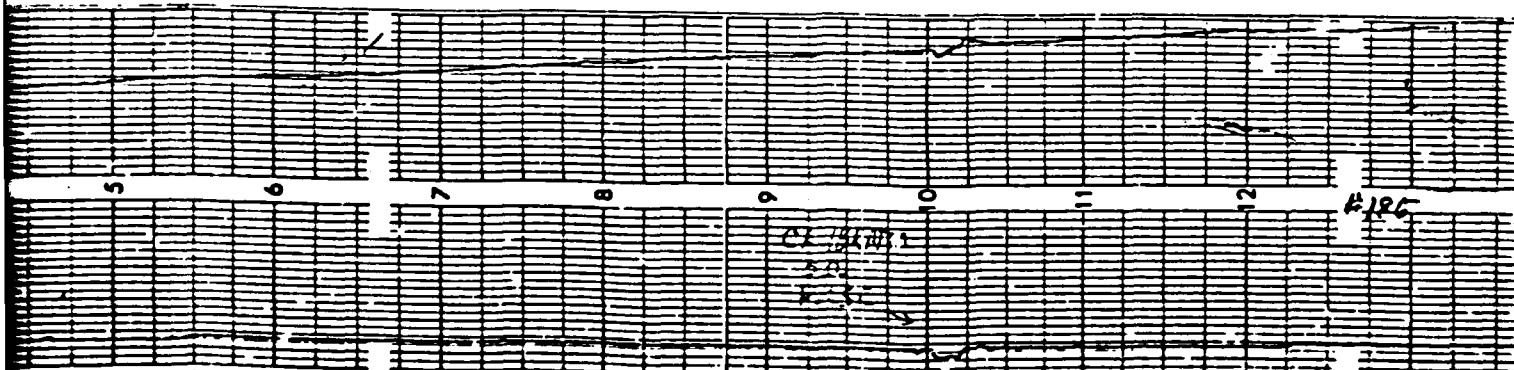
Crystal #194



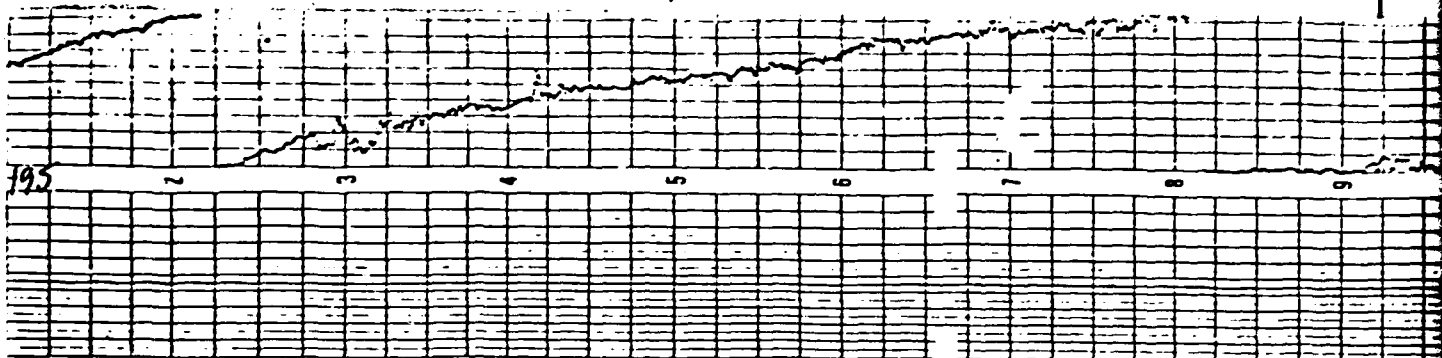
Crystal #192



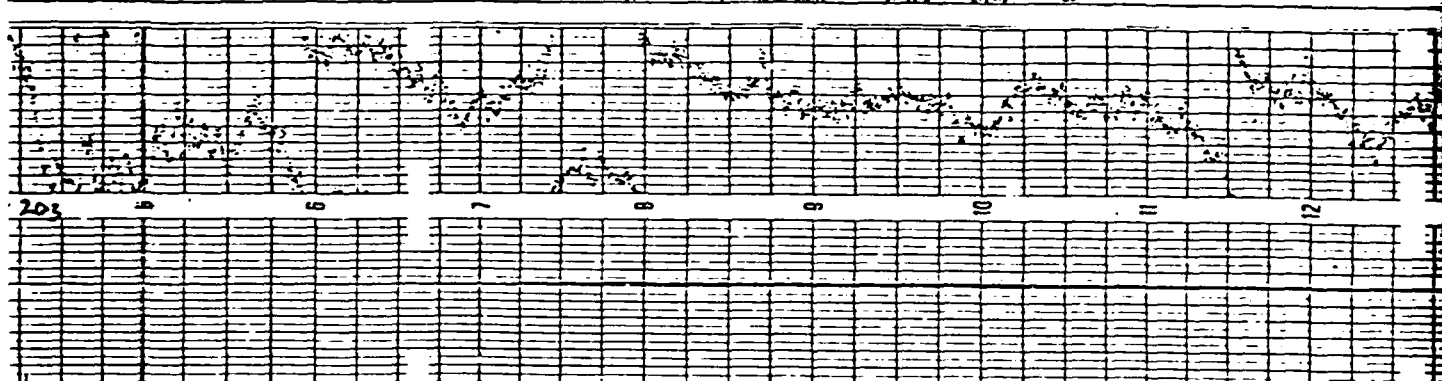
Crystal #197



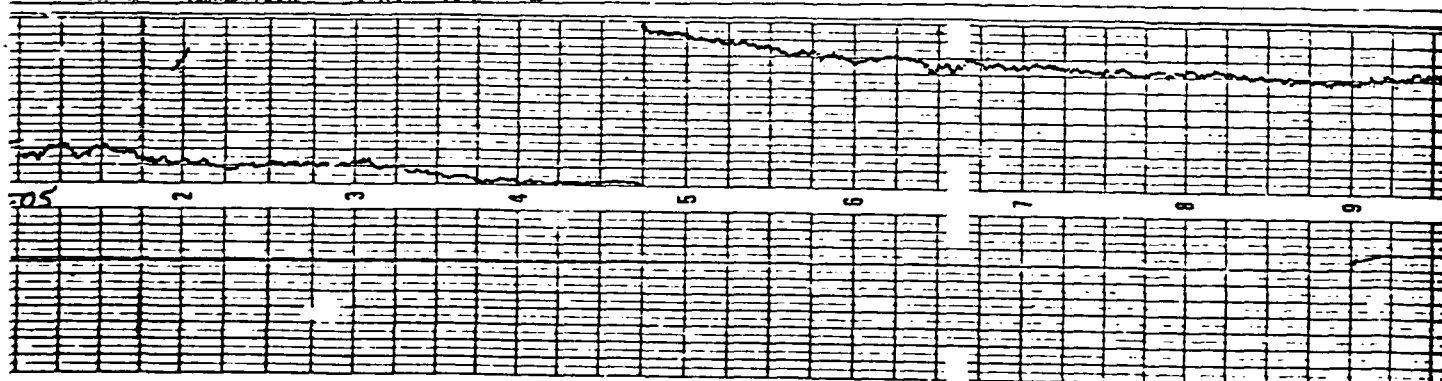
Crystal #186



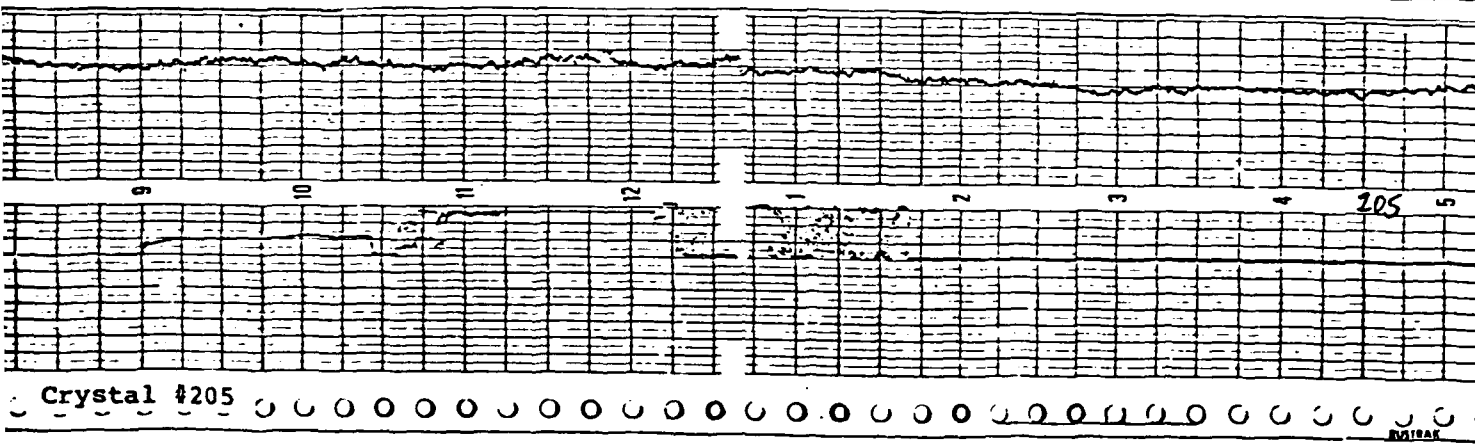
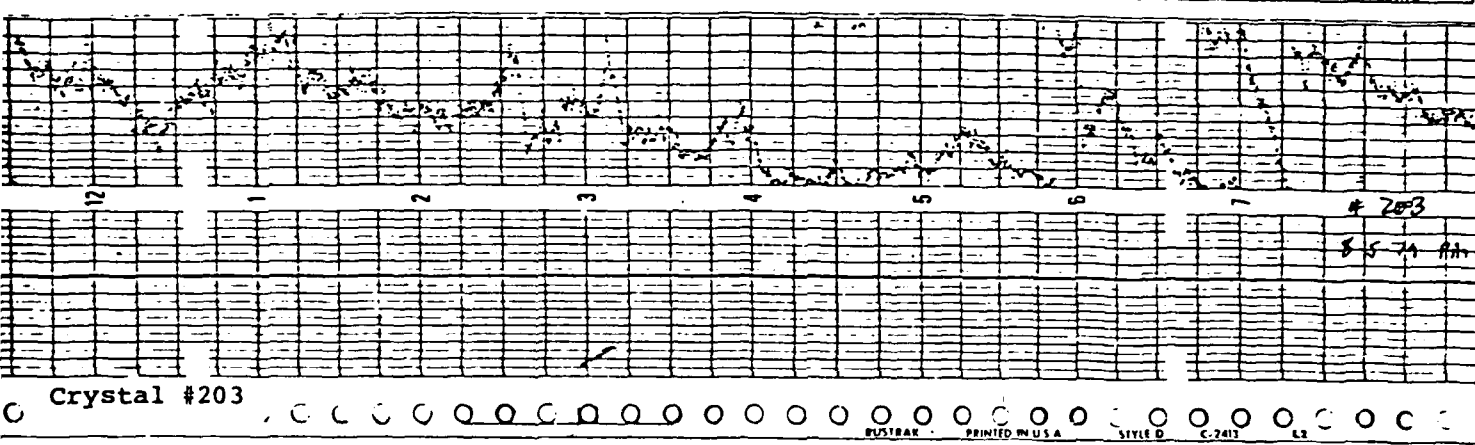
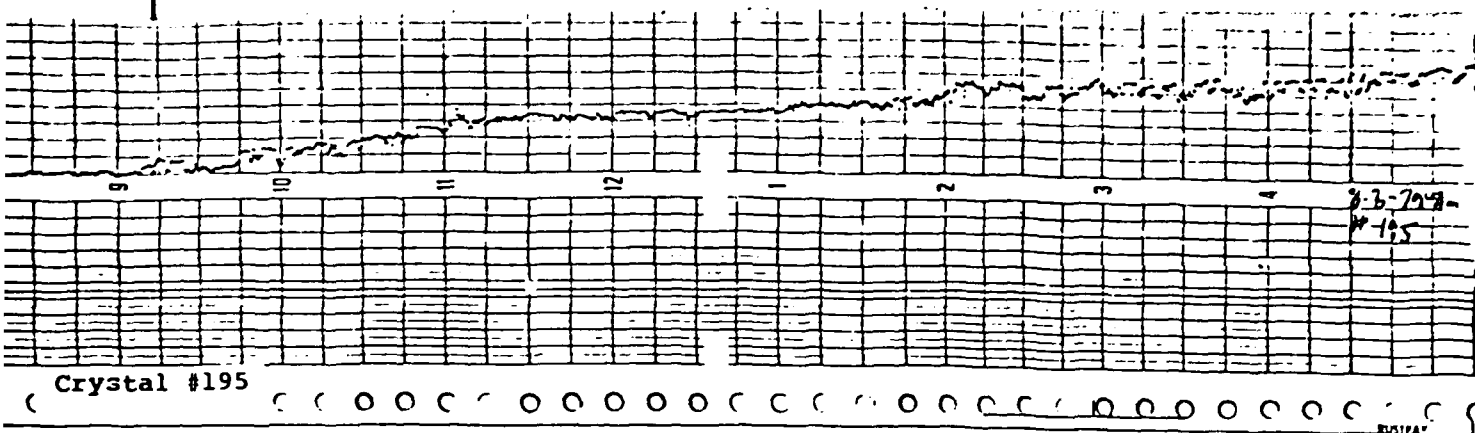
Crystal #1



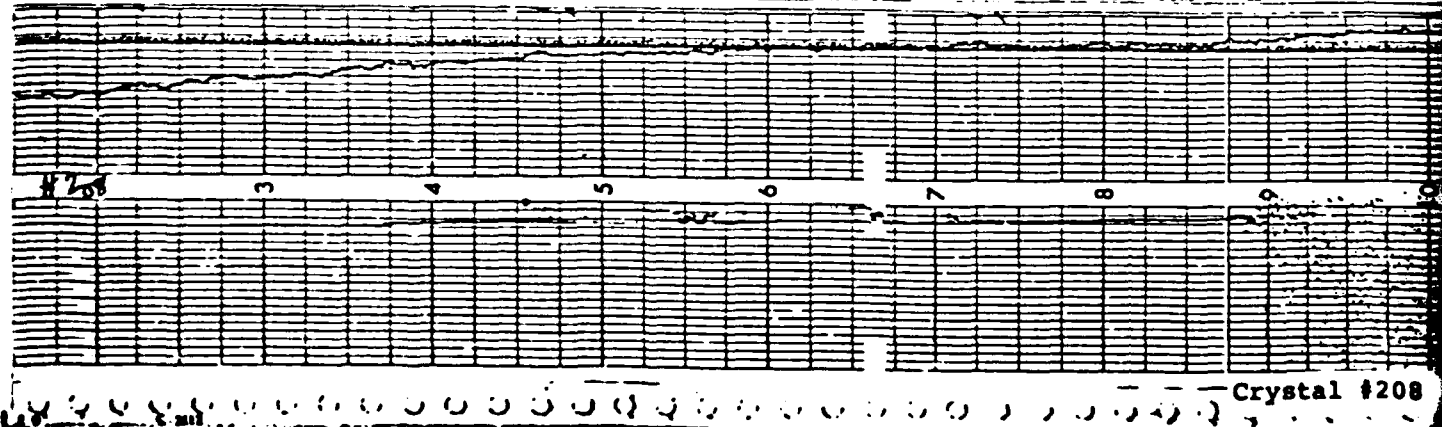
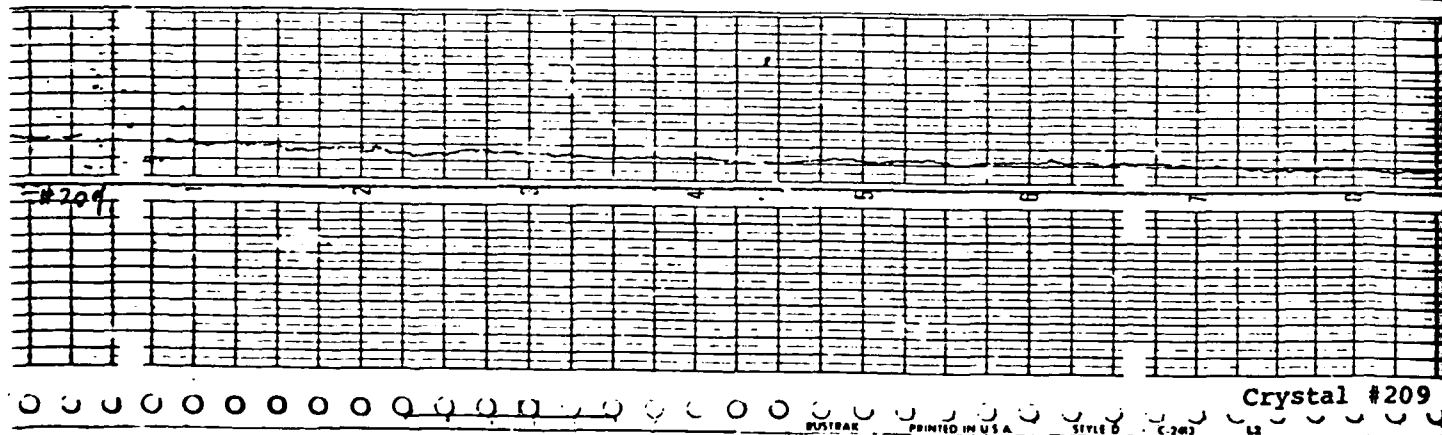
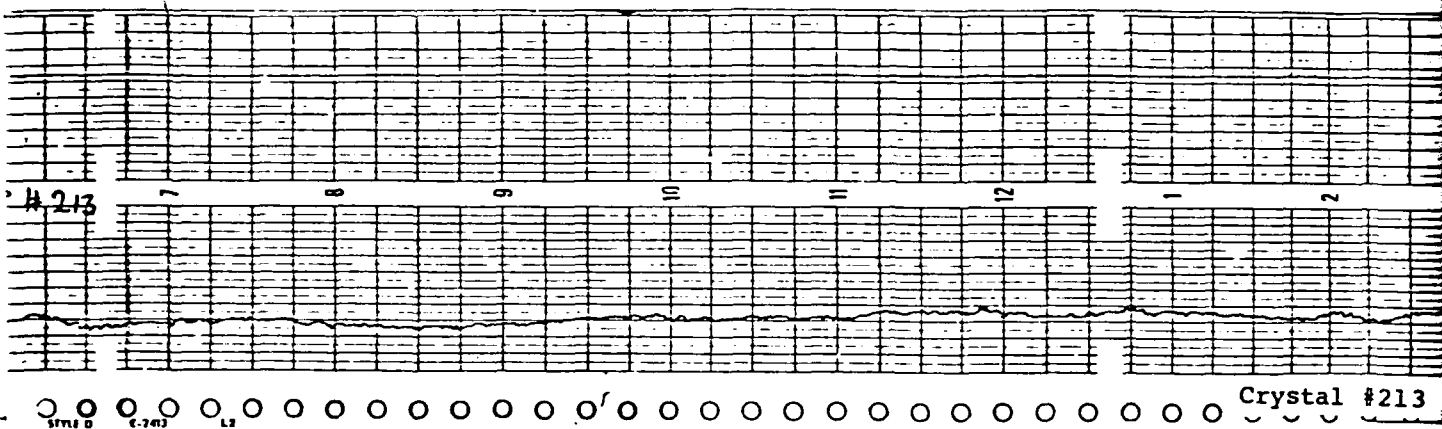
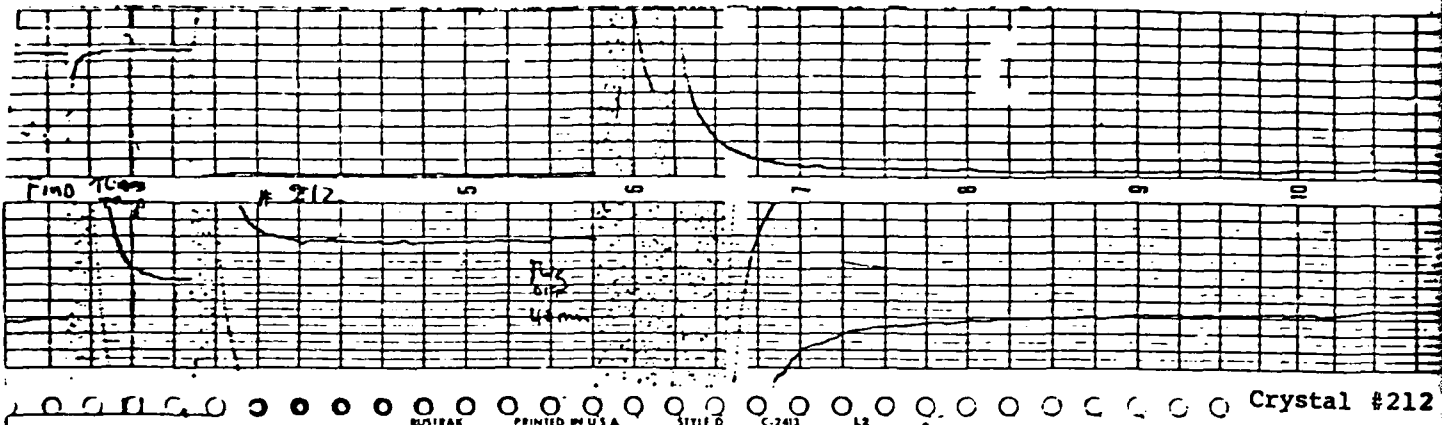
Crystal #20

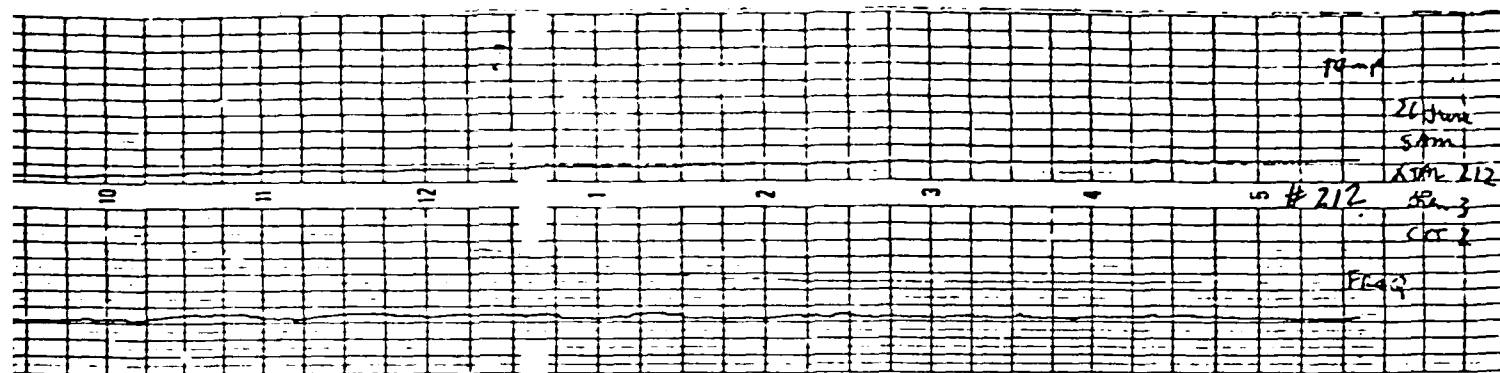


Crystal #205

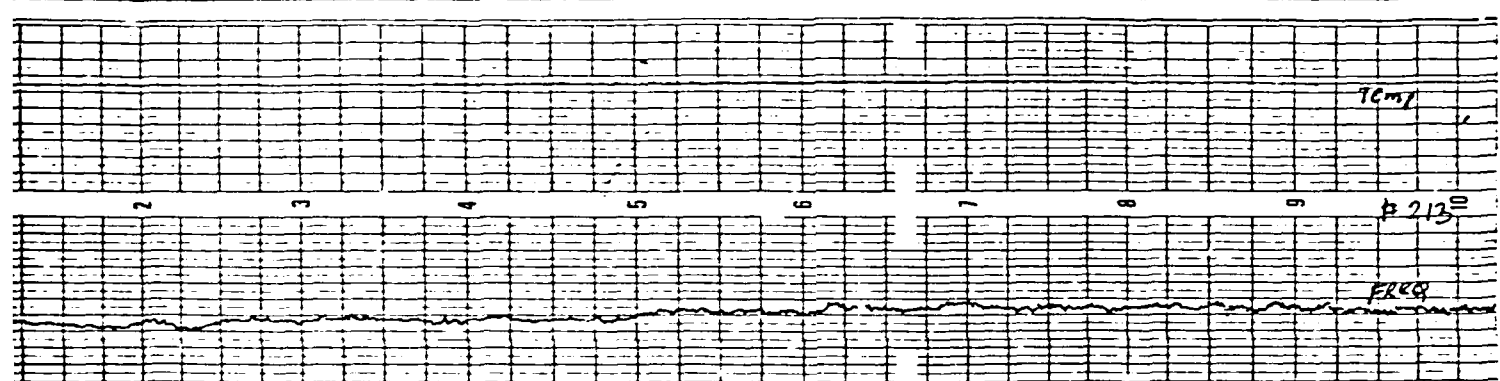


2

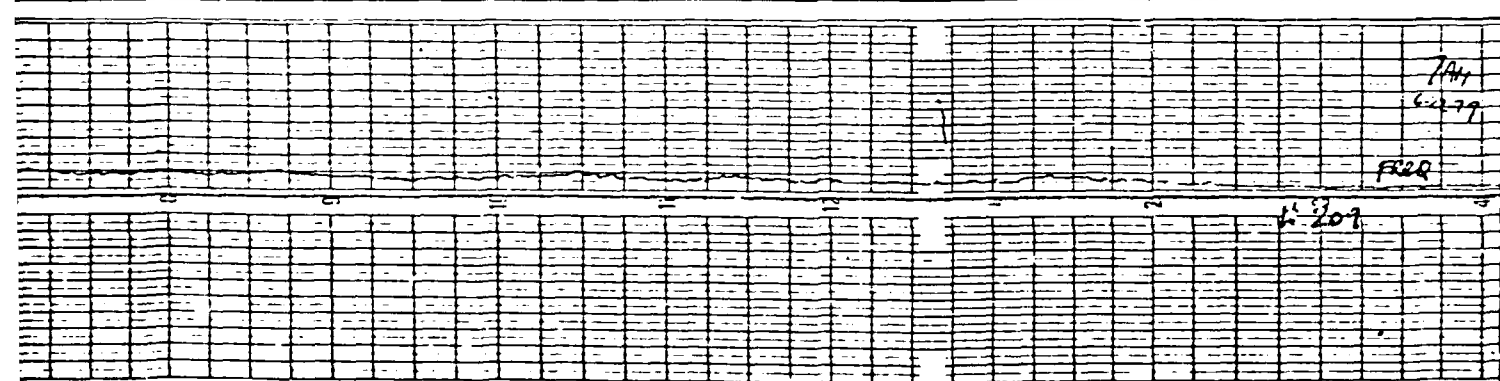




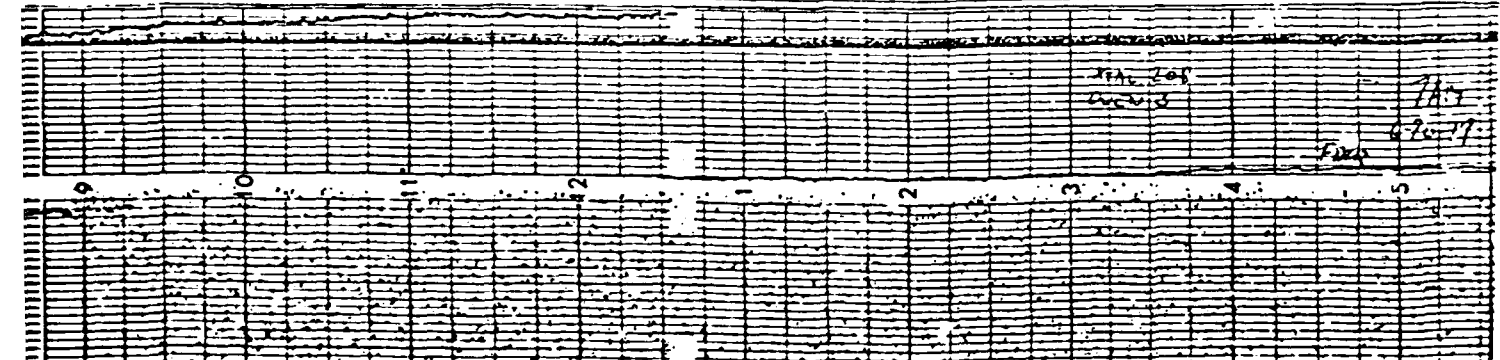
Crystal #212



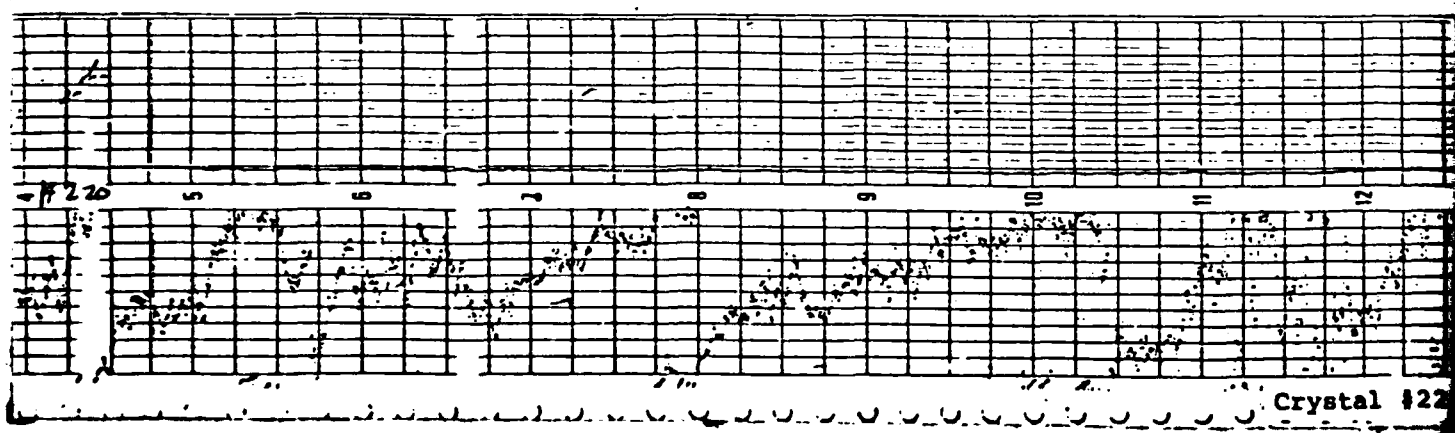
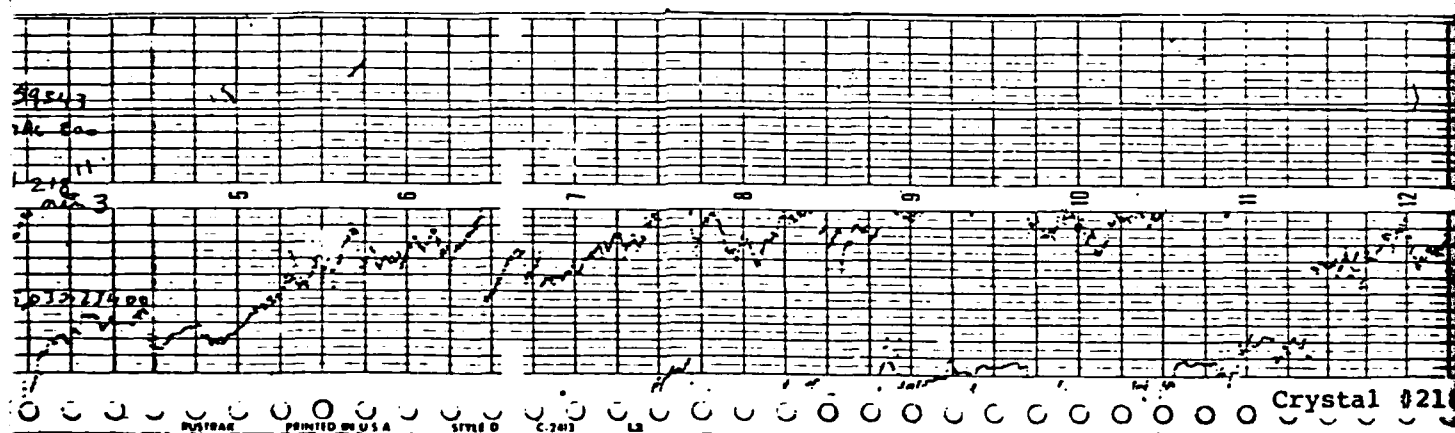
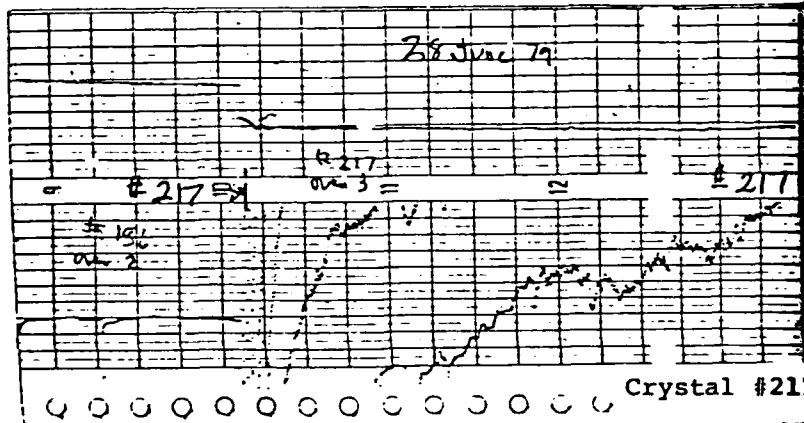
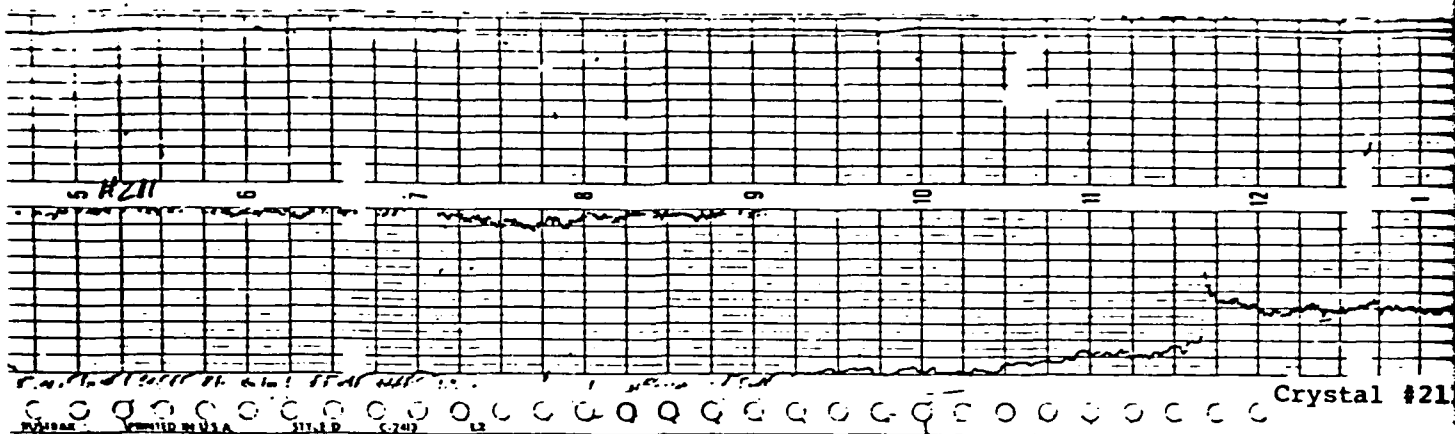
Crystal #213

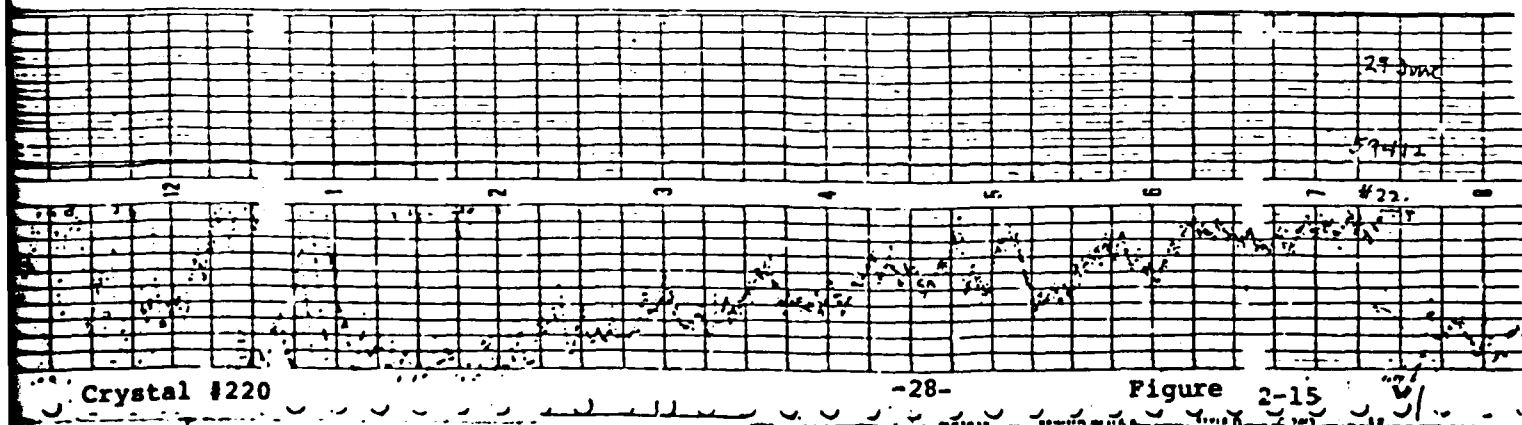
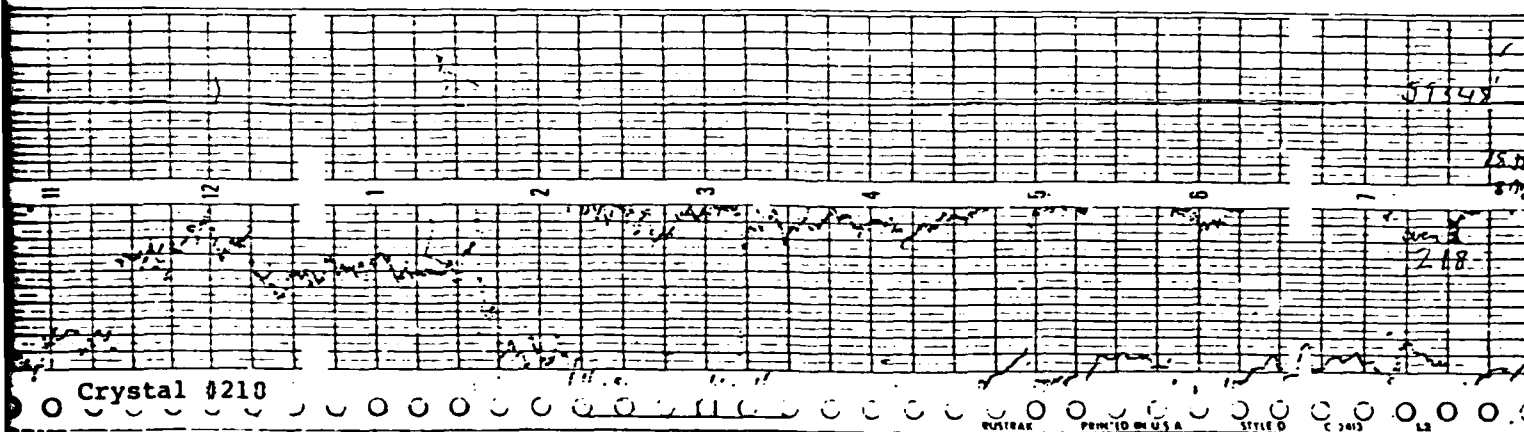
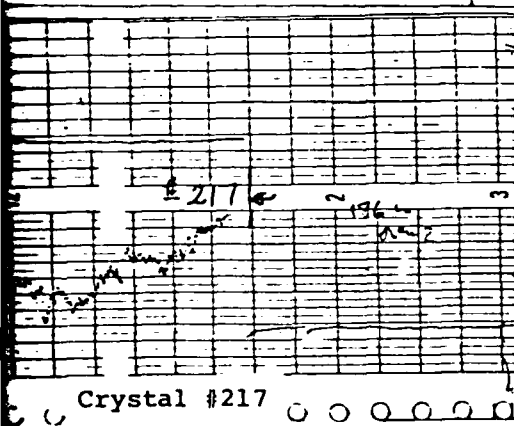
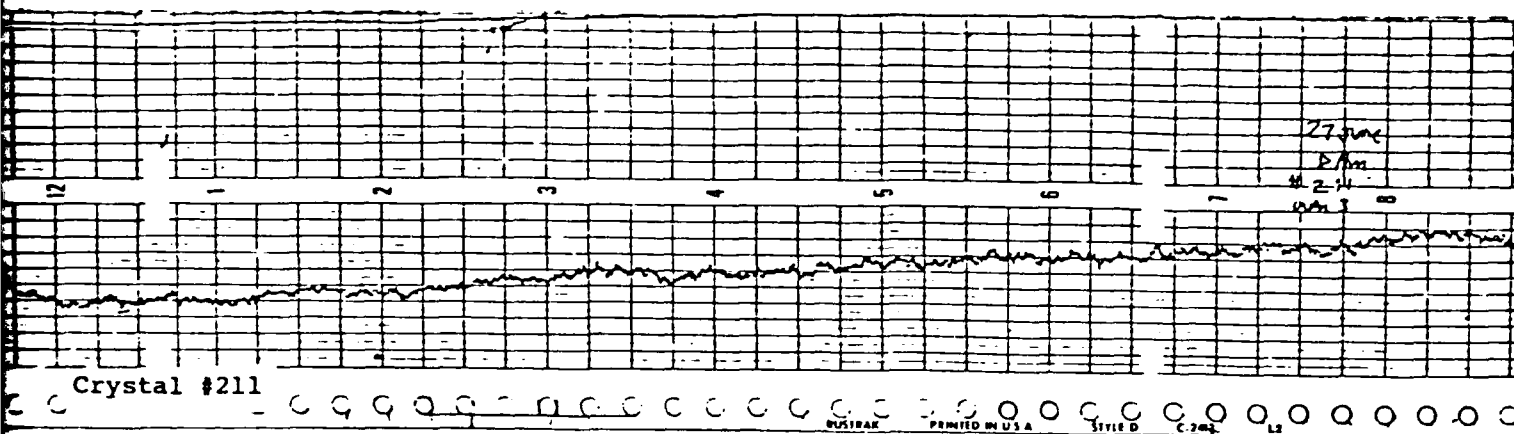


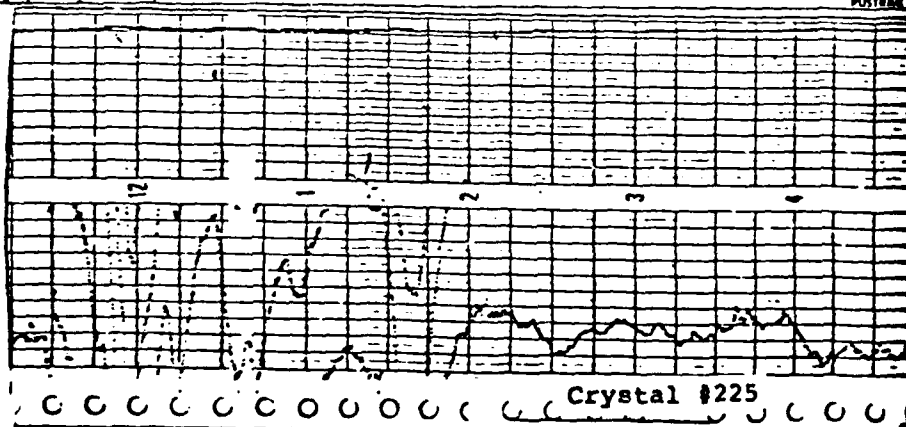
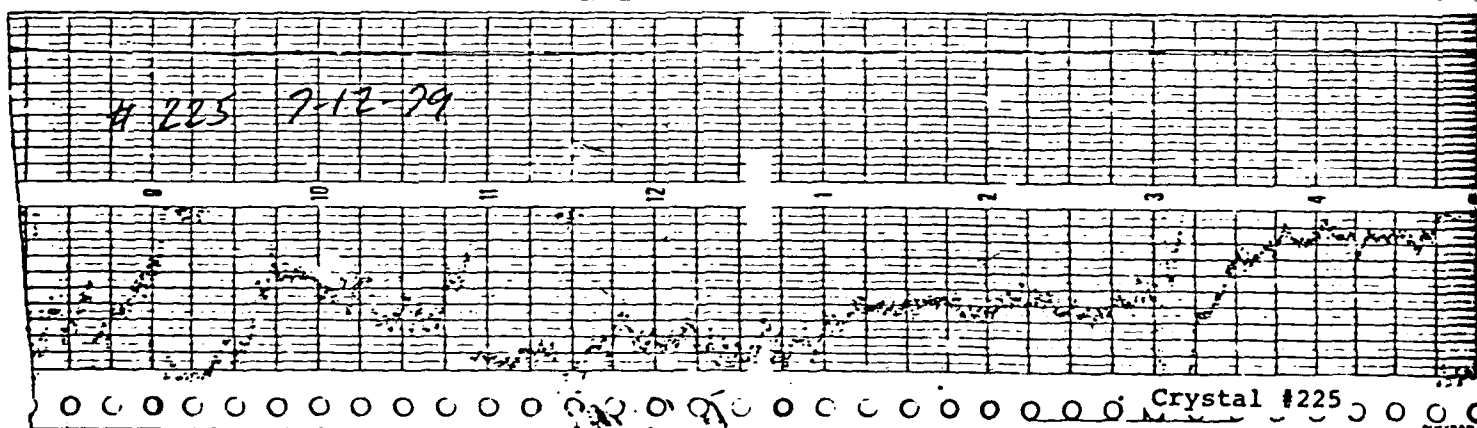
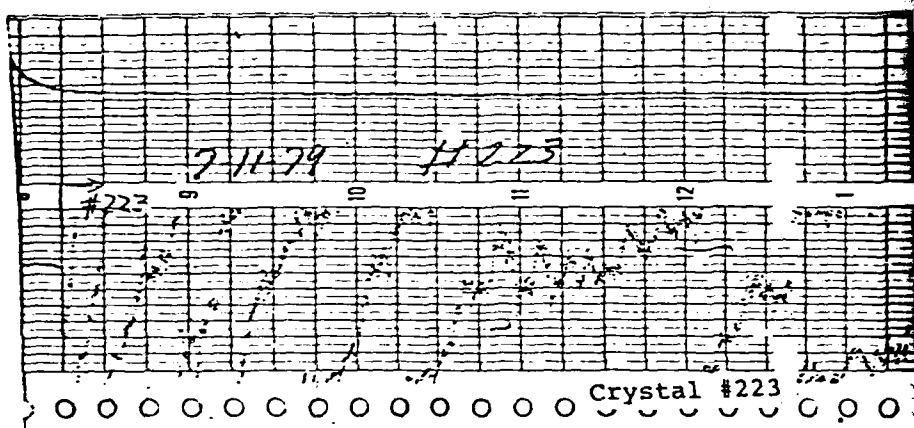
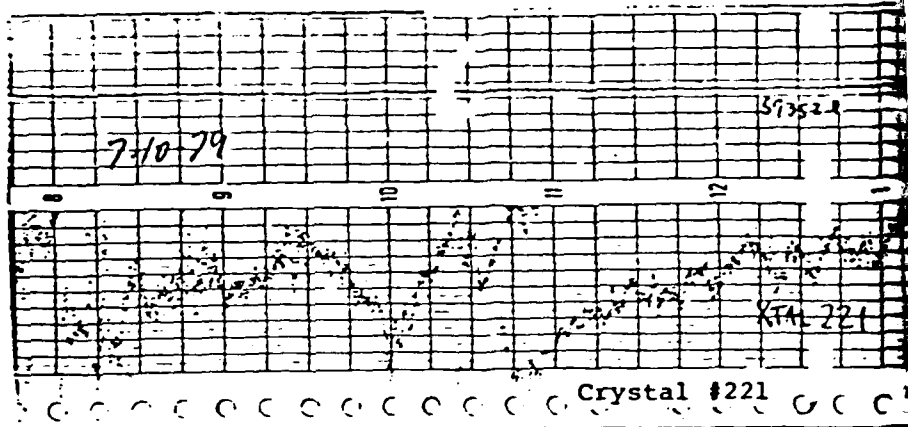
Crystal #209

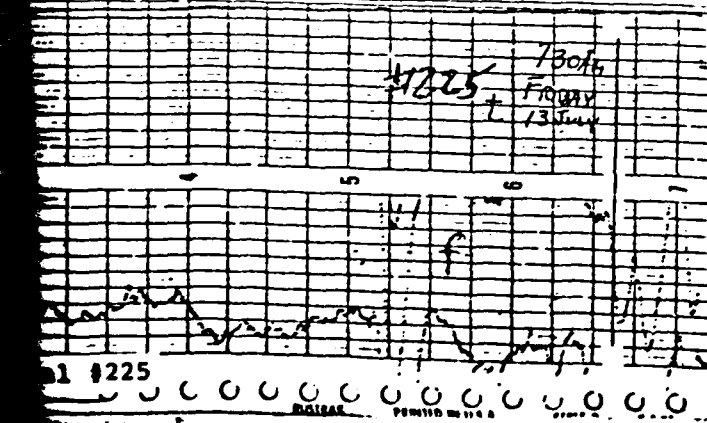
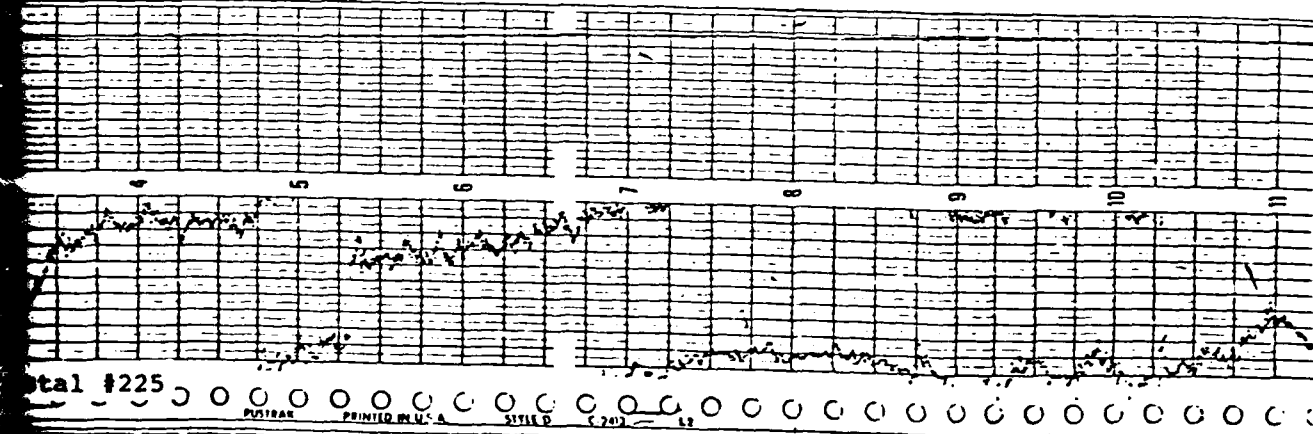
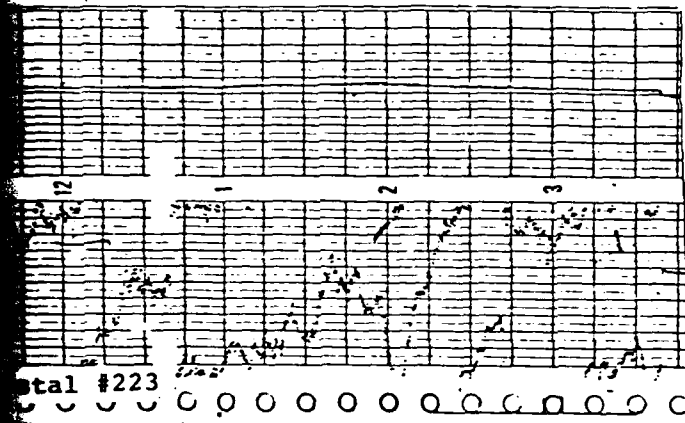
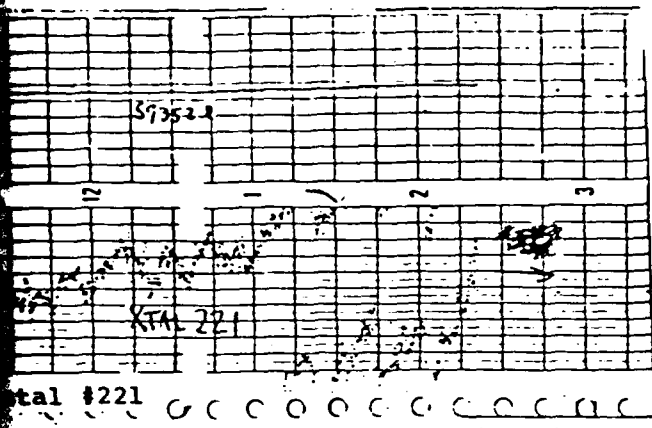


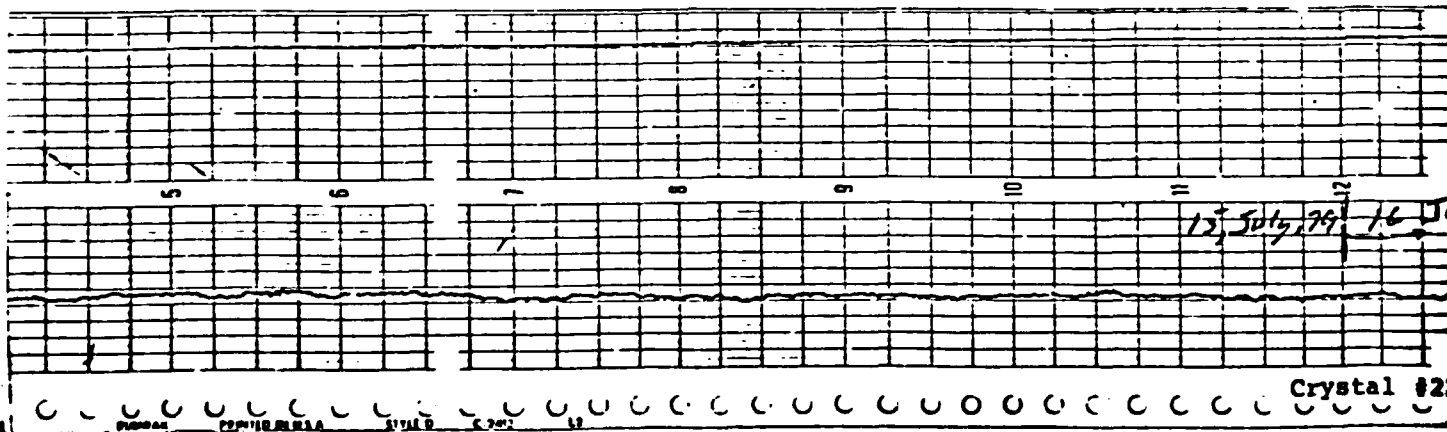
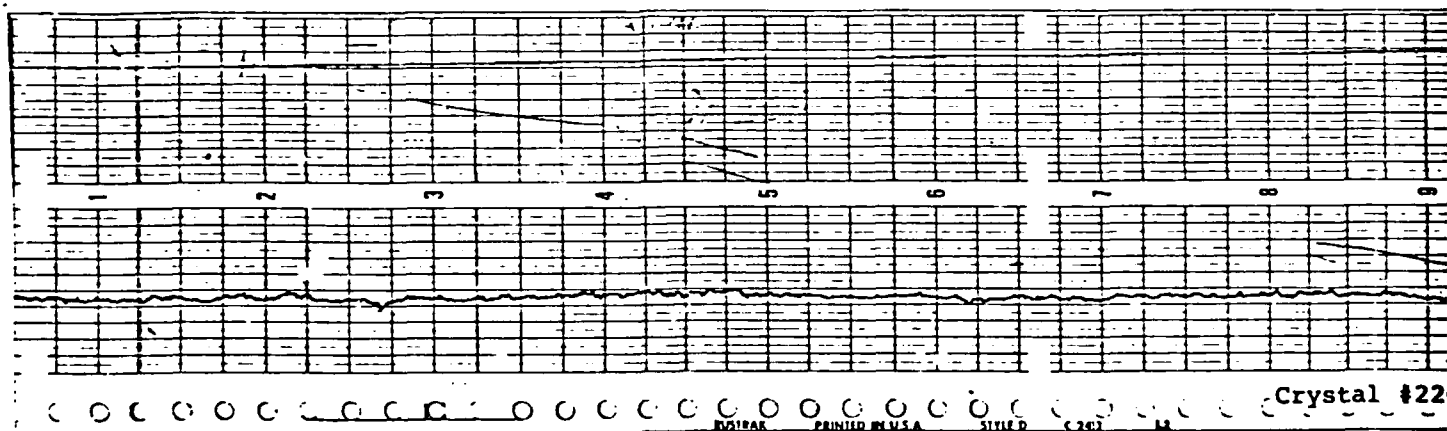
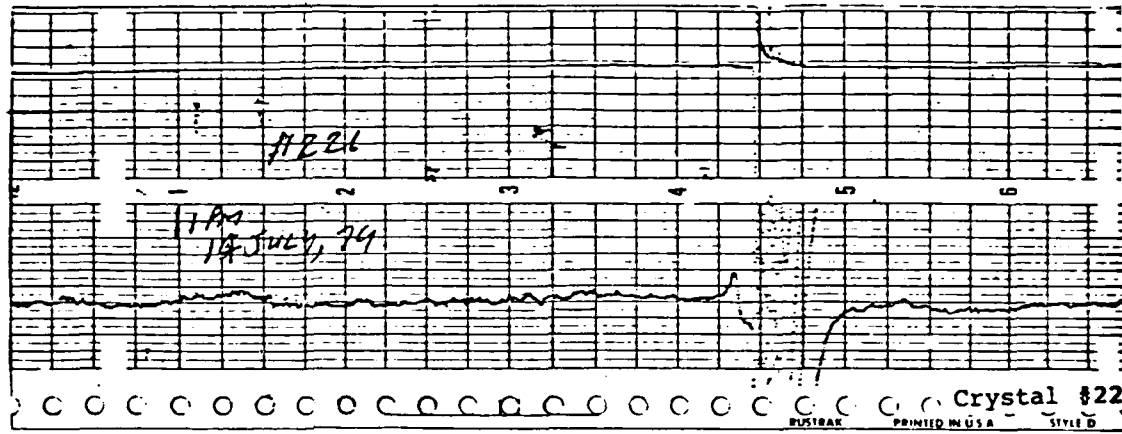
Crystal #208

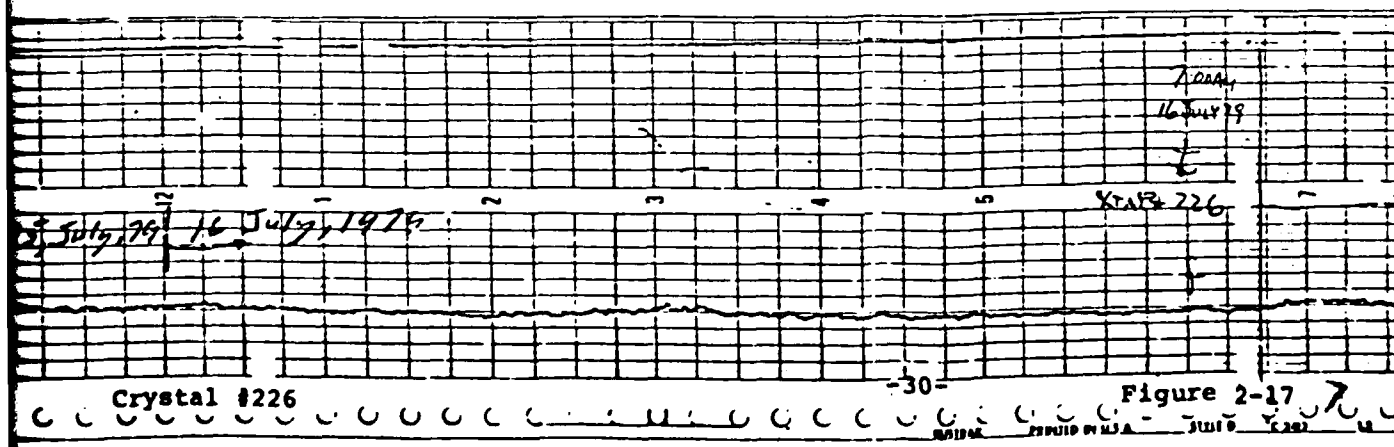
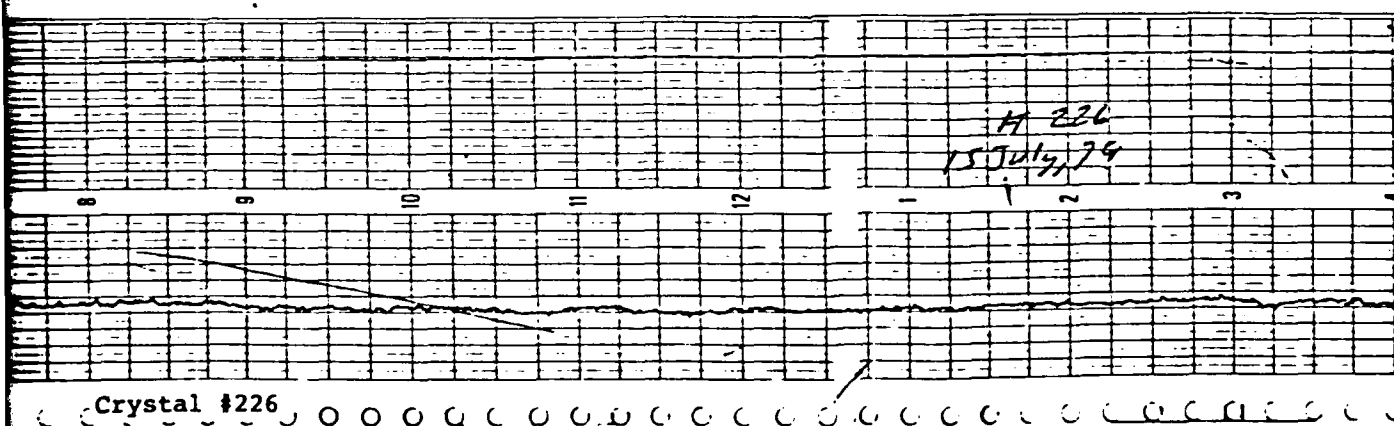
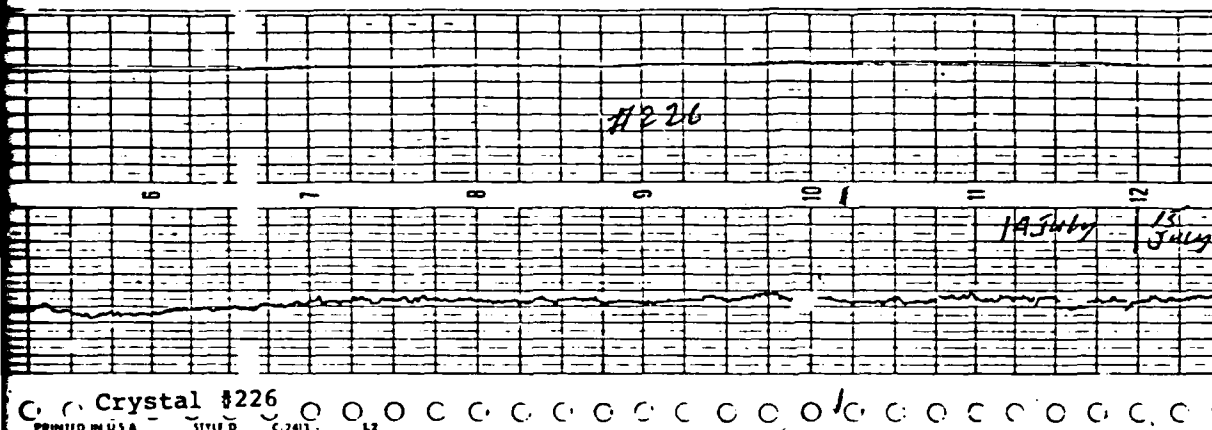


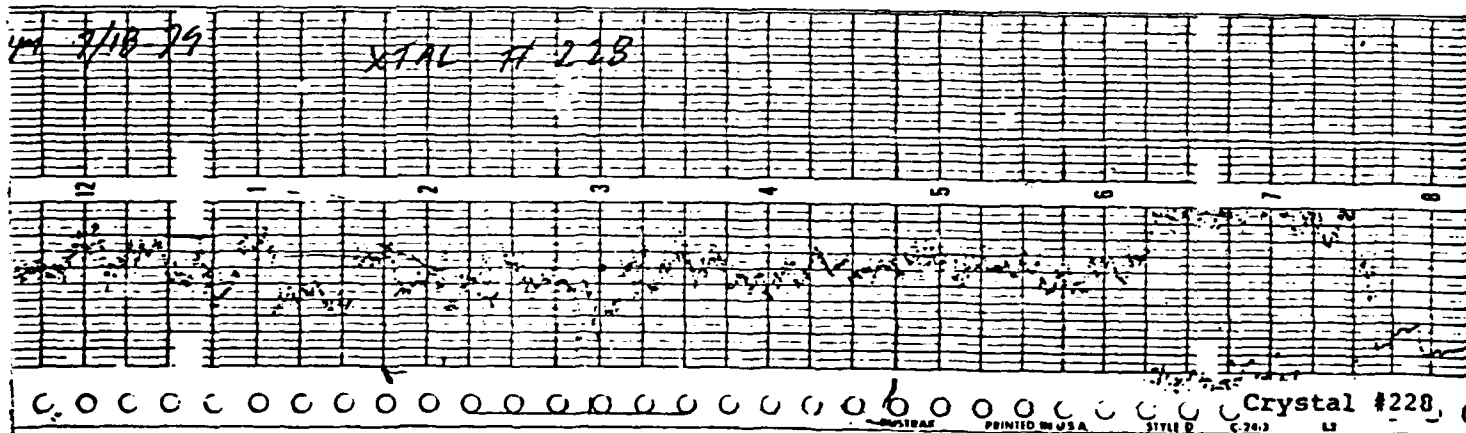
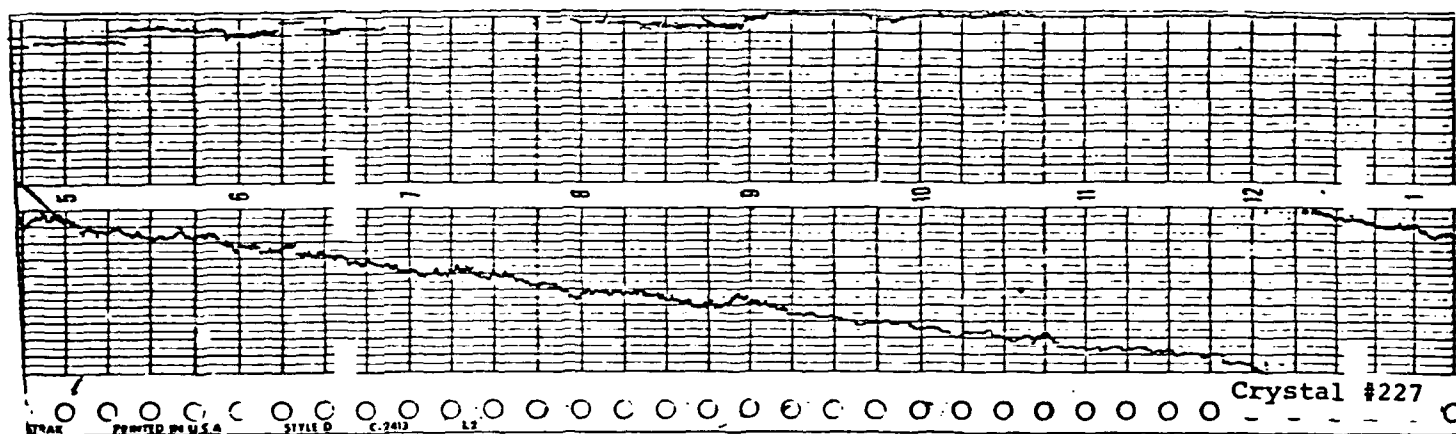
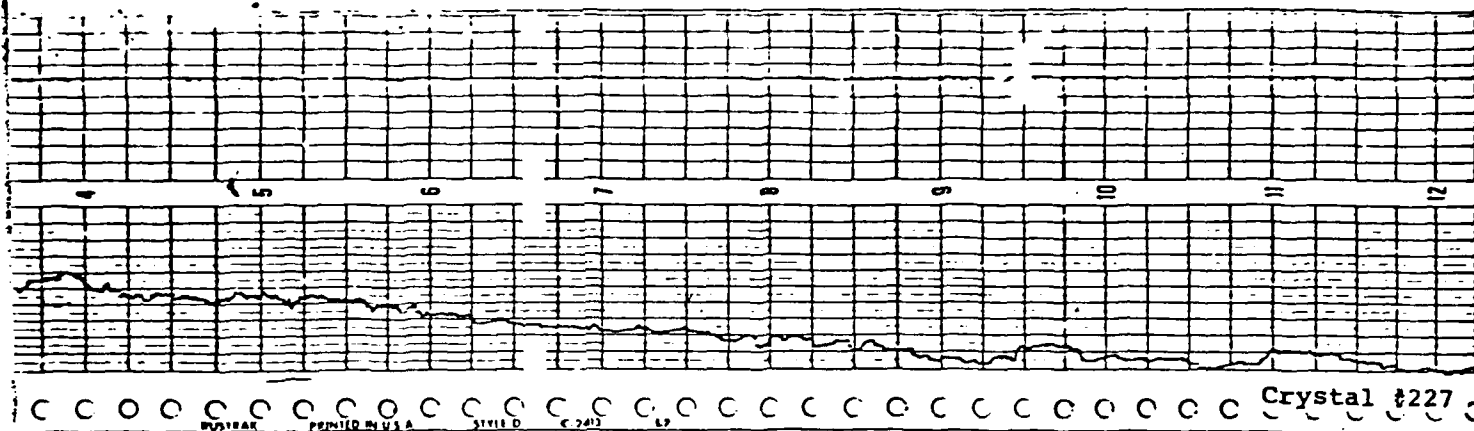


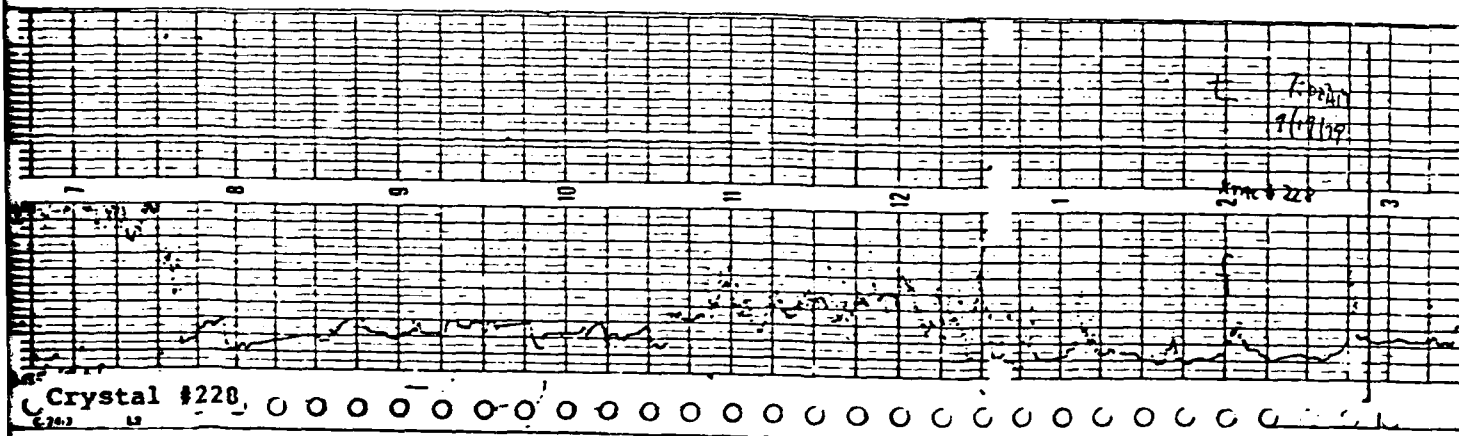
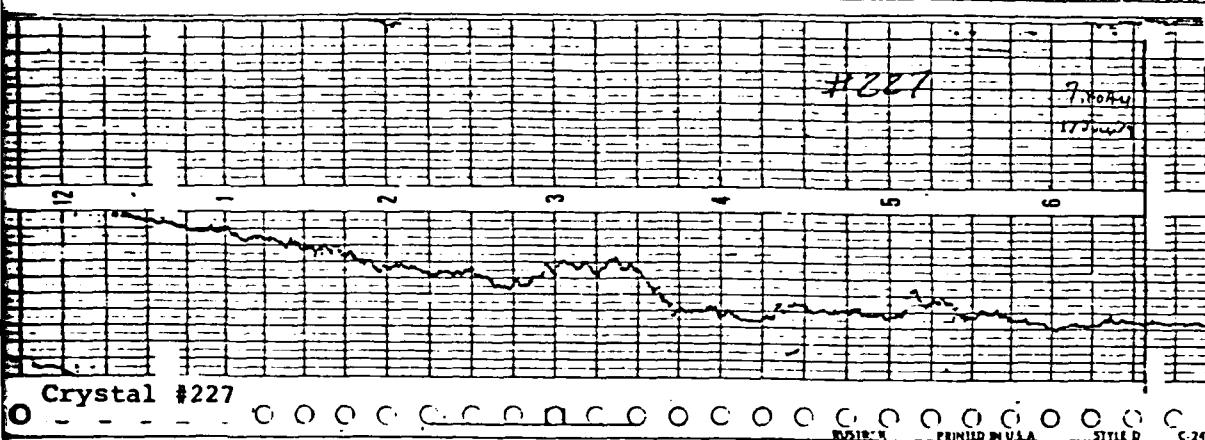
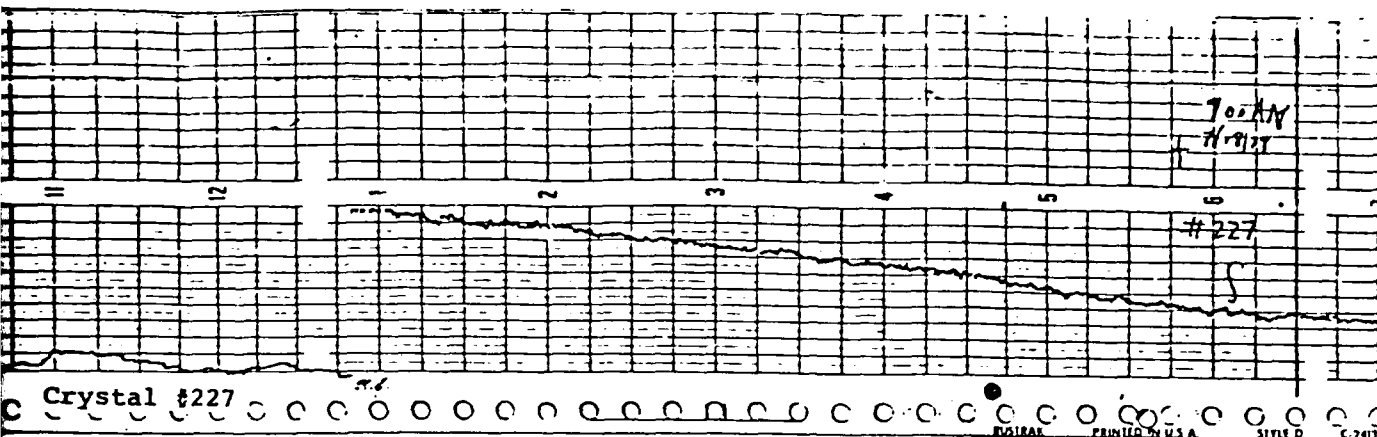




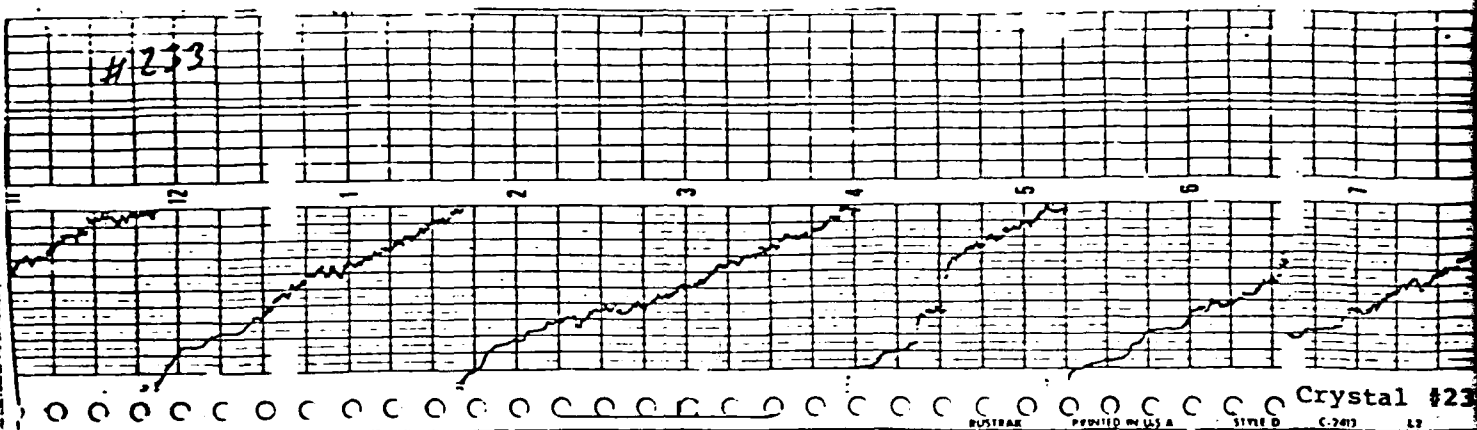








#233

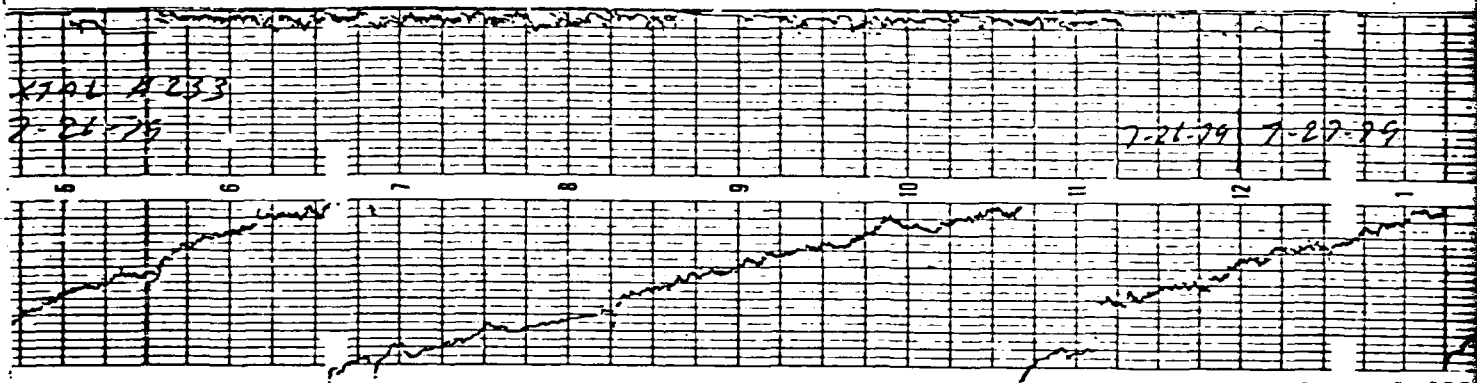


Crystal #23

PRINTED IN U.S.A. STYLE D C-7403 L2

#233
7-21-79

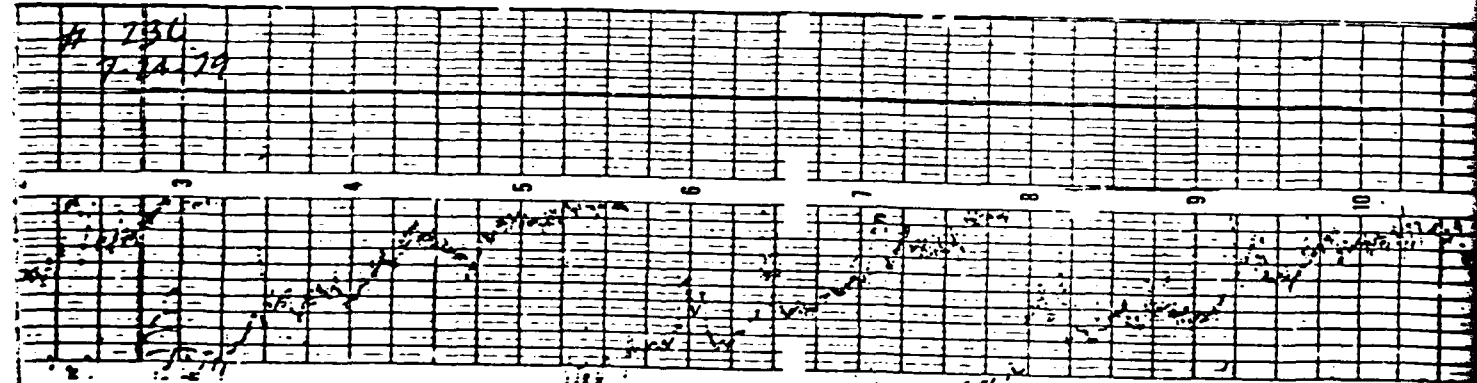
7-21-79 7-27-79



Crystal #23

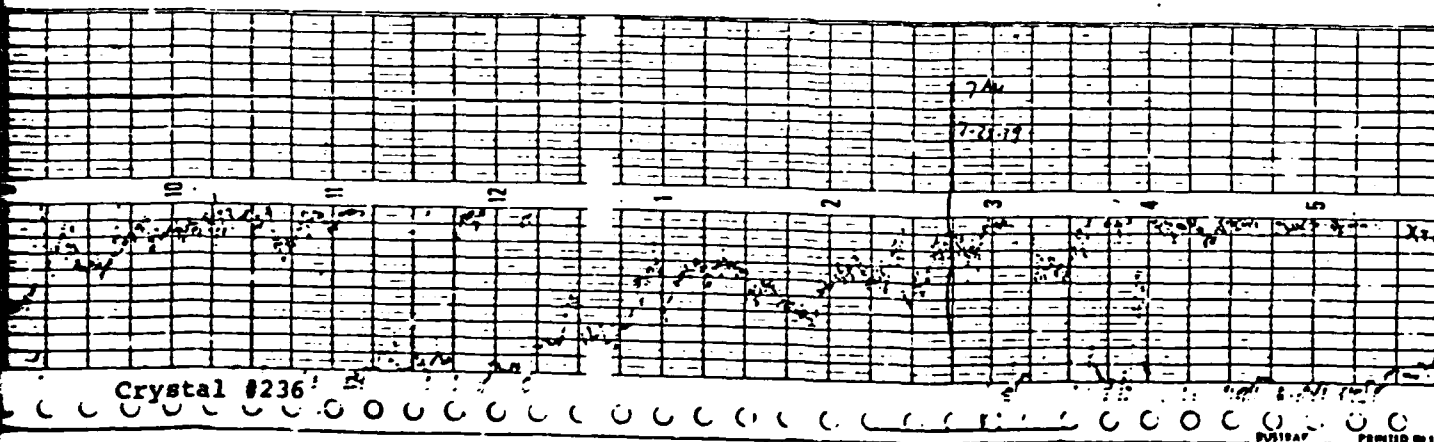
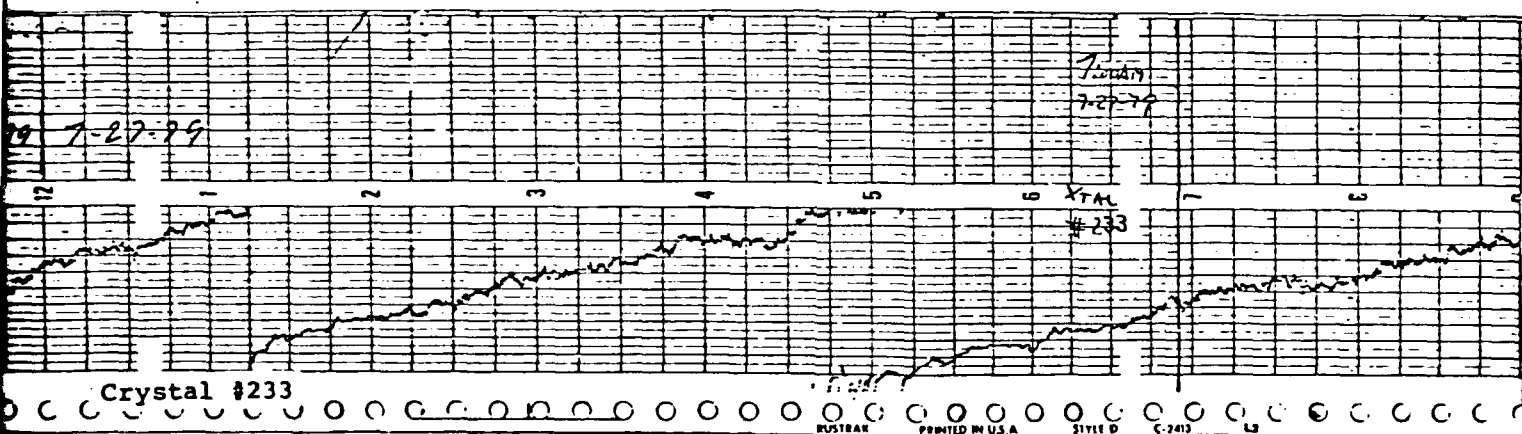
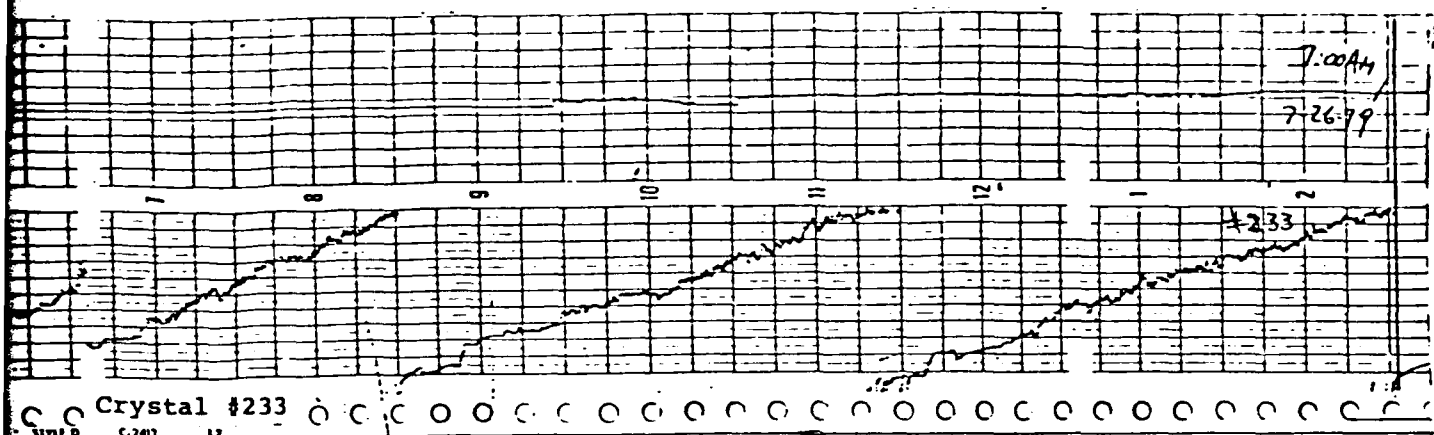
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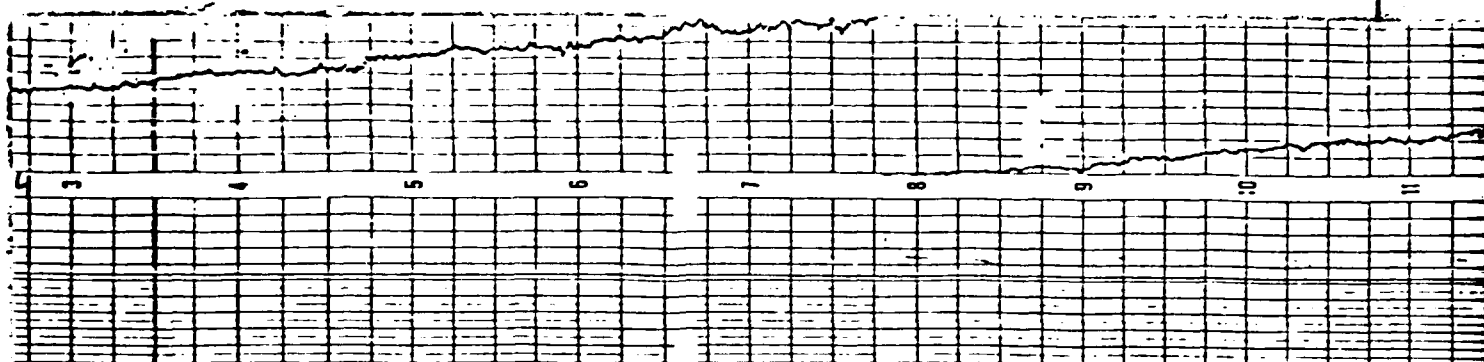
#230
7-24-79



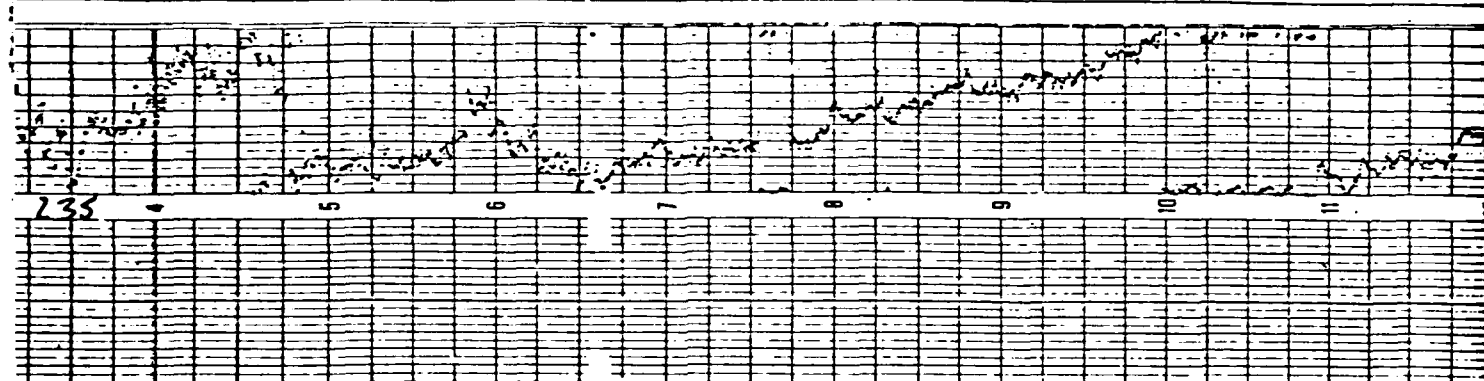
Crystal #23

PRINTED IN U.S.A. STYLE D C-7403 L2

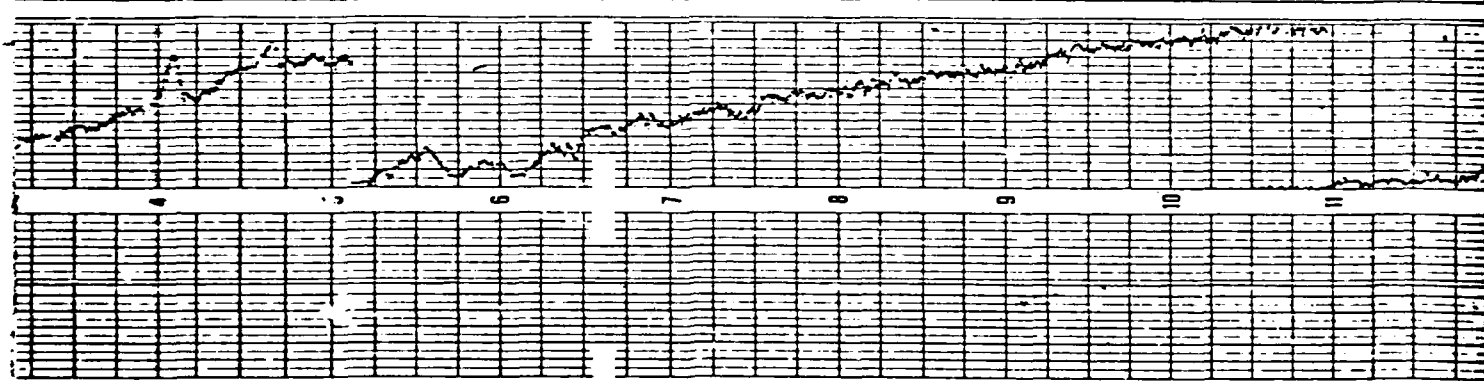




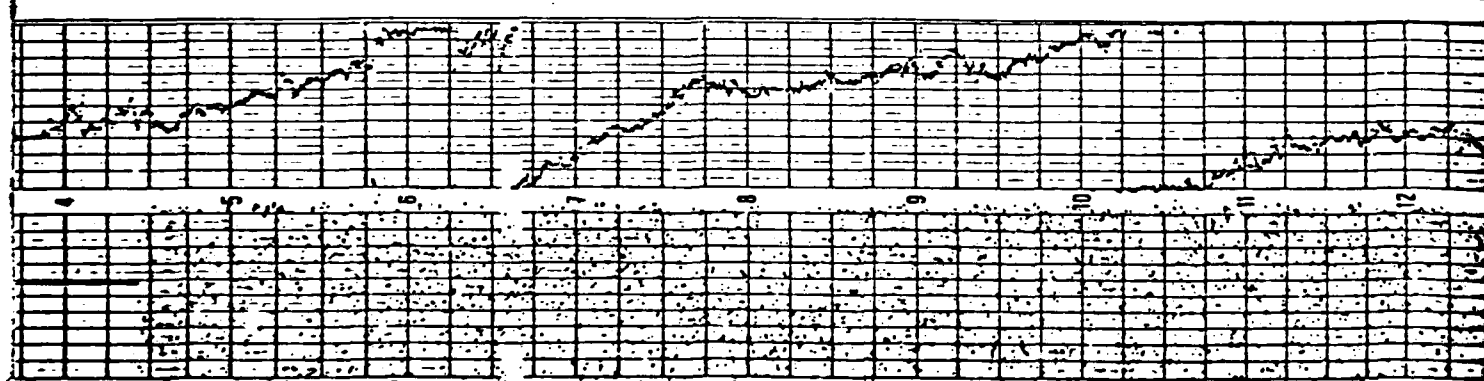
Crystal #2
PULSTAR PRINTED IN U.S.A. STYLE D C-7412 L2



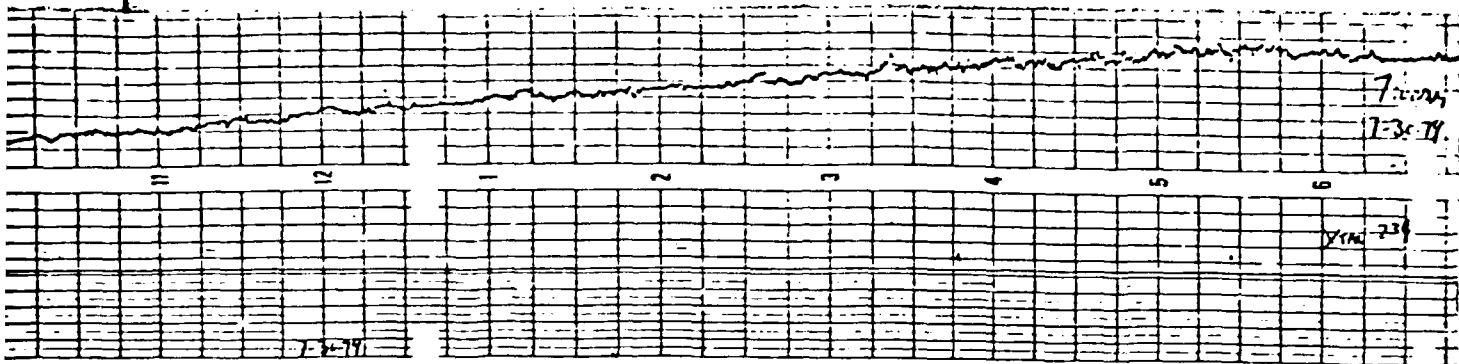
Crystal #2
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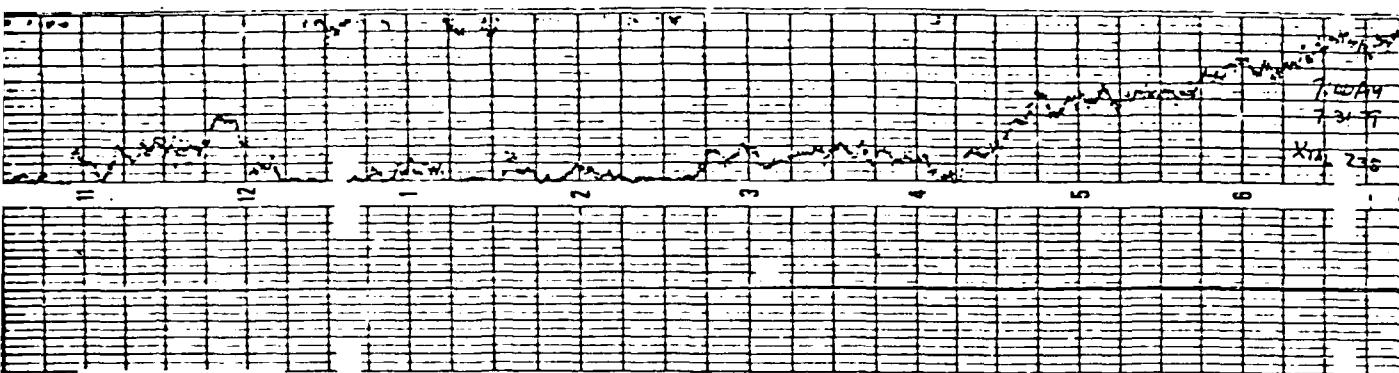
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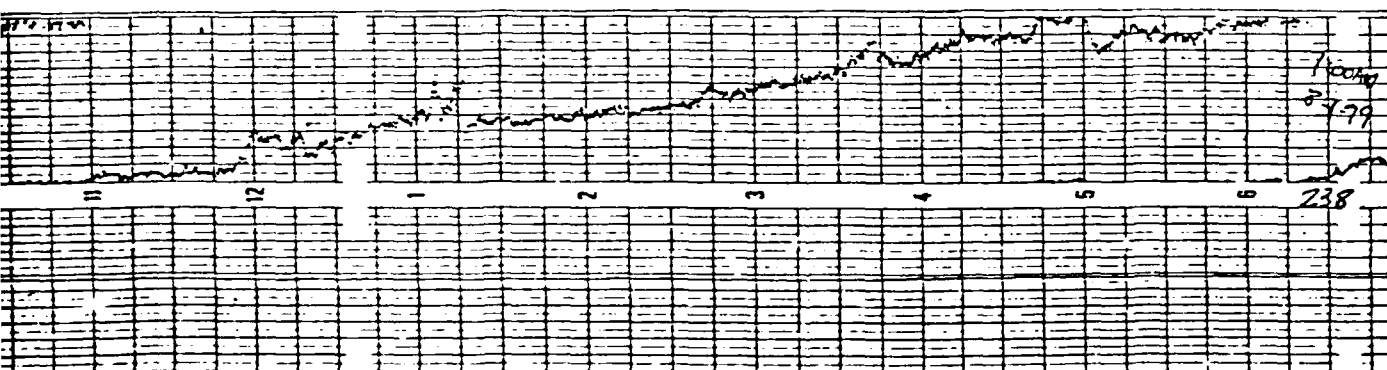
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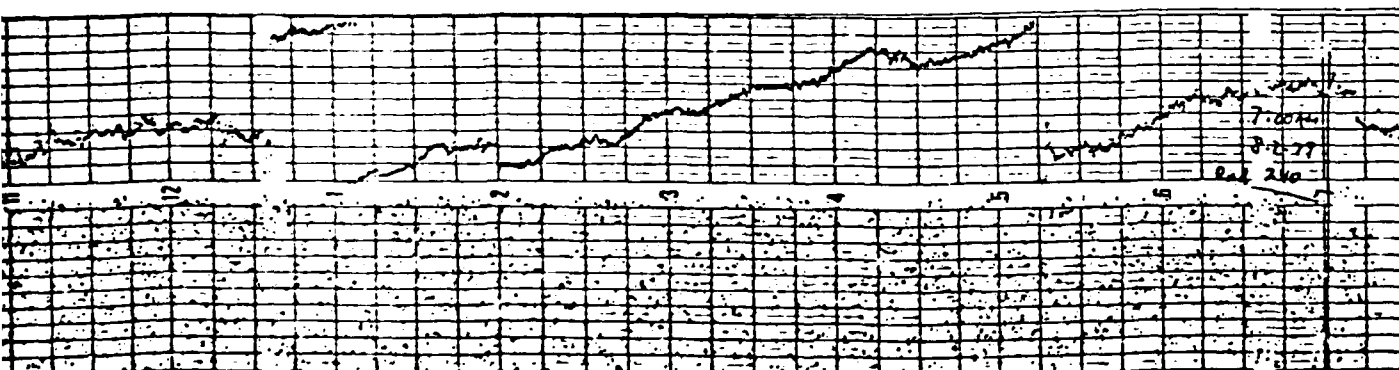
Crystal #234



Crystal #235



Crystal #238



Crystal #240

Figure 2-20

2

The short term stability is better than that observed with the best fundamental crystals (CR 186 and CR 212) received so far from G.E.N.D. The crystal is presently aging at a rate of 1×10^{-8} per day; crystals manufactured by this process are expected to require 30 days to achieve minimum aging rates.

(4) FUNDAMENTAL CRYSTAL RETRACE MEASUREMENT. An important crystal performance requirement for the TMXO application is the frequency recovery at -40°C ambient. Repeatability of the stabilized frequency after warm up or retrace, was measured for crystal CR 186 with excellent results. The "no-reactance" oscillator circuit (Figure 2-6) was used for this measurement. The oscillator was operated with its Dewar flask mounted within a climate chamber at -40°C ambient. The temperature decay time constant (oven off) of the oven/flask is normally 4 hours, requiring about 16 hours after oven shutdown for the crystal temperature to reach the -40°C ambient temperature.

In order to expedite the cool down portion of the retrace cycle, provision was made to allow insertion of a "cold finger" which would penetrate the Dewar cork and contact the oven outer surface, providing complete cool down in 4 hours, with a minimum physical disturbance of the oscillator/oven assembly. The results of the test are shown in Table 2.

Table 2-2

Cycle #	Stabilized Frequency	Δf From Start	$\Delta f/f$ From Start
Start	5,114,614.54041 Hz	---	---
First	5,114,614.53821 Hz	-0.00220 Hz	-4.3×10^{-10}
Second	5,114,614.54117 Hz	+0.00076 Hz	$+1.5 \times 10^{-10}$
Third	5,114,614.54320 Hz	+0.00279 Hz	$+5.5 \times 10^{-10}$
Fourth	5,114,614.53997 Hz	-0.00044 Hz	-0.86×10^{-10}
Fifth	5,114,614.54287 Hz	+0.00246 Hz	$+4.8 \times 10^{-10}$

The TMXO specification requires $\frac{\Delta f}{f}$ from start to be within $\pm 3 \times 10^{-9}$.

(5) EVALUATION OF 10 MHZ THIRD OVERTONE CRYSTALS. A breadboard TMXO oscillator configured for third overtone 10 MHz crystals, was constructed and installed in a test oven. The crystal test circuit provided a load capacity of about 60 pf. The circuit is shown in Figure 2-21 and will be described in the following section. The oven temperature was slewed at 4 m°C/Sec through the turn temperature, and turn temperature and minimum frequency of the oscillator were recorded for sixteen 10 MHz third overtone crystals. The results of these measurements are shown in Table 2-3.

Crystal 10R139 did not oscillate, presumably because of the large effective series resistance (64 ohms) of this unit. Seven units showed turn temperatures below the 84°C minimum turn temperature.

There was a wide dispersion of the measured turn temperature frequencies. Most of the units with acceptable turn temperatures are already too high in frequency with the 60 pf load capacitance used in the measurement, and operation with the nominal 30 pf load capacity would increase frequency about 100 Hz more. Crystal 10R131 appears to be the only unit with acceptable turn temperature and frequency.

No determination has yet been made of the short term stability performance of the third overtone crystals.

(6) TMXO CRYSTAL OSCILLATOR CIRCUIT DEVELOPMENT. During this period, a crystal oscillator circuit, suitable for use in the TMXO, having reduced power requirements has been under development. Figure 2-21 shows the schematic of the oscillator.

The cascode configuration of the output stage was selected to minimize output circuit shunt capacity, and thereby provide the necessary 0.17 VRMS output level with minimum current consumption. A similar circuit, driven in parallel, provides excitation for the AGC detector. The hot carrier diodes were chosen to minimize the AC voltage (and current consumption) required to control the oscillator transistor current, to maintain constant crystal excitation.

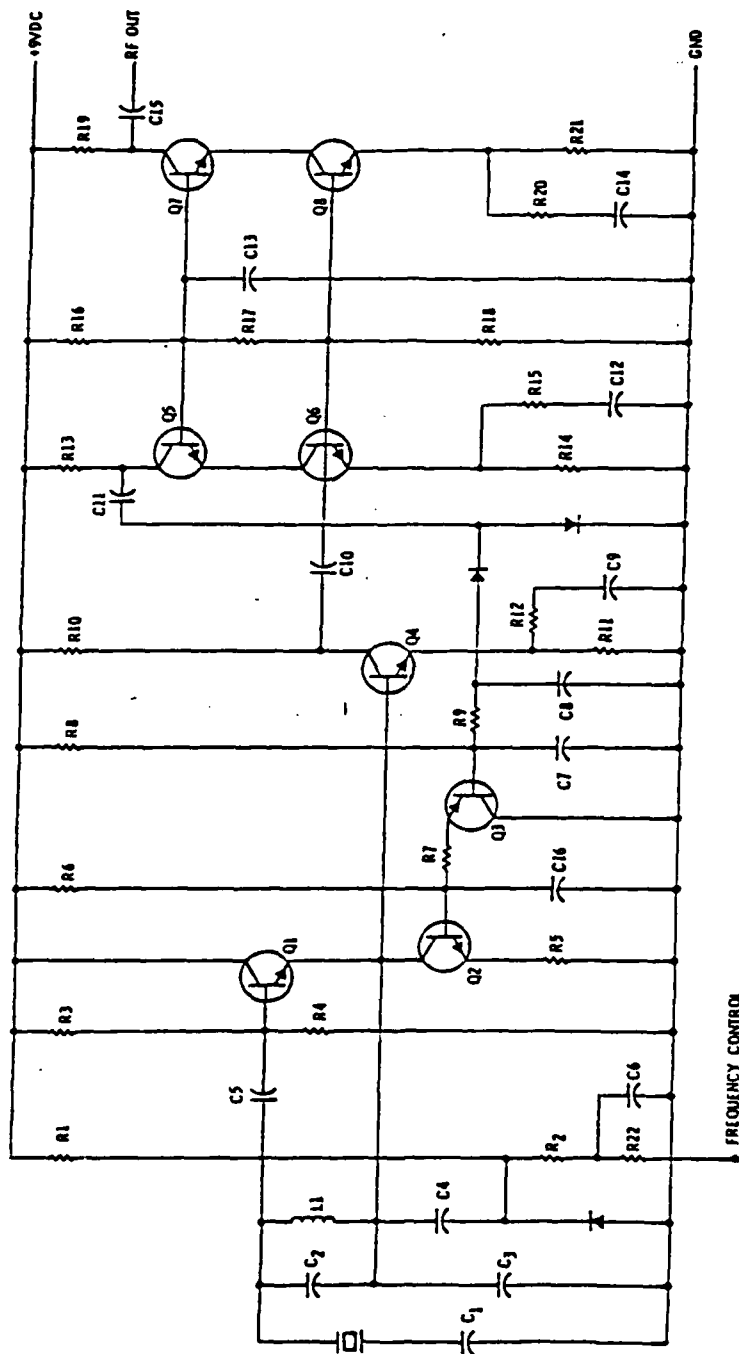


FIGURE 2-21 TMXO Oscillator Circuit Schematic

Table 2.3

Crystal Status (1 October 1979)*					
Crystal S/N	Frequency MHz	Date Received	Short Term Stability	Turn Temp	Freq. of oscillator @ Turn Temp
10R89	10.0(3rd)	5/10/79	Not Tested	80.2°C	9,999,537 Hz
10R112		6/1/79		90.4	9,998,673
10R114		6/1/79		84.7	10,008,878
10R119		7/2/79		86.3	10,000,221
10R120		7/2/79		85.7	10,000,219
10R123		8/7/79		87.0	10,000,034
10R126		8/7/79		89.2	10,000,108
10R131		7/2/79		84.2	9,999,886
10R133		8/7/79		82.9	9,999,162
10R134		7/2/79		83.2	9,999,845
10R136		7/2/79		85.3	9,999,568
10R138		7/2/79		80.0	10,000,038
10R139		7/2/79		Does Not Oscillate	
10R140		8/7/79		78.3	9,999,911
10R141		8/7/79		78.7	9,999,838
10R145		8/7/79		82.9	9,998,055

*These units were experimental devices produced during the early phases of the TMXO crystal unit development program at GEND (see footnote on page 16).

The current requirement is about 1 ma at 9 VDC. The principal difference between the 5 MHz and the 10 MHz versions of the oscillator circuit confined to the values of C1, C2 and C3 and the inclusion of L1 for the third overtone 10 MHz version.

The 5 MHz version breadboard has exhibited a preliminary short term and long term stability performance similar to the "no reactance" test oscillators.

(7) LONG TERM STABILITY EVALUATION.

A) Preliminary Measurements. During this period, work has begun on evaluation of retrace and long term aging of components other than the crystal which impact on oscillator frequency stability. The method used involves the verification of performance of a "no reactance" oscillator with an aged crystal. Candidate reactive elements are introduced in series with the crystal, and change of performance attributed to the candidate element is determined. Because the crystal series reactances are large, the effect of candidate reactances are diminished, requiring good short term stability as well as considerable measurement time to detect differences and characterize components. Before investing considerable time in a candidate reactive element, a preliminary measurement of start up and aging (duration of a few days) has been completed on a number of devices listed below.'

Candidate Reactive Elements

ATC-100	Porcelain Capacitor
VC2A	Ceramic Trimmer Capacitor
MV1660	Varactor Diode
1 μ H	Toroidal Coil

The results to date are acceptable with the exception of the ceramic trimmer capacitor which contributed frequency discontinuities of $\frac{\Delta f}{f} = 1 \times 10^{-9}$, and relatively severe initial aging.

B) Drift Contribution of Porcelain Chip Capacitors. Crystal CR 186 was installed in oven #3 for long term aging Evaluation. The "no reactance" circuit Figure 2-6, was used, with an ATC-100 110 pf porcelain capacitor in series with the crystal. The circuit operated undisturbed from 20 June through 1 August 1979.

Figure 2-22 shows the frequency drift recorded during the interval, and indicates a final slope of $\frac{\Delta f}{f} = 3.3 \times 10^{-10}/\text{day}$, which is considerably higher than the TMXO specification value of $2 \times 10^{-10}/\text{week}$. In order to ascertain if a significant drift results from the capacitor, the capacitor was shorted out and the drift monitored for another 10 days. The rate without the capacitor was $+2.6 \times 10^{-10}/\text{day}$; the difference ($0.7 \times 10^{-10}/\text{day}$) assigned to the capacitor indicates a rate of change of capacity equal to -1.5 ppm/day . Subsequent measurements, using different circuits, crystals and capacitor values have provided capacitance drift values between -2 ppm/day and -3 ppm/day for the ATC -100 porcelain capacitors. These results are cause for concern because they indicate that capacitor drift alone will cause fundamental oscillator circuit aging to exceed the $2 \times 10^{-10}/\text{week}$ specification.

C) Drift Dependence on Crystal and Crystal Excitation. The data shown in Figure 2-22 represents crystal CR 186 operated at approximately 0.7 ma crystal current. To determine dependence of drift rate on crystal excitation level, the crystal current was then reduced to 50 μa and drift rate again monitored for 10 days. The measured rate at 50 μa (without series capacitor) was $+2.4 \times 10^{-10}/\text{day}$, indicating essentially no change of drift rate over this range of excitation.

In order to investigate dependence of drift rate on crystals, crystal CR 186 was replaced with crystal CR 212 which had previously demonstrated good short term stability. The measurement was taken after 10 days with preliminary results indicating a drift rate of $+1.2 \times 10^{-10}/\text{day}$, about half that measured for CR 186, but still about 5 times specification values.

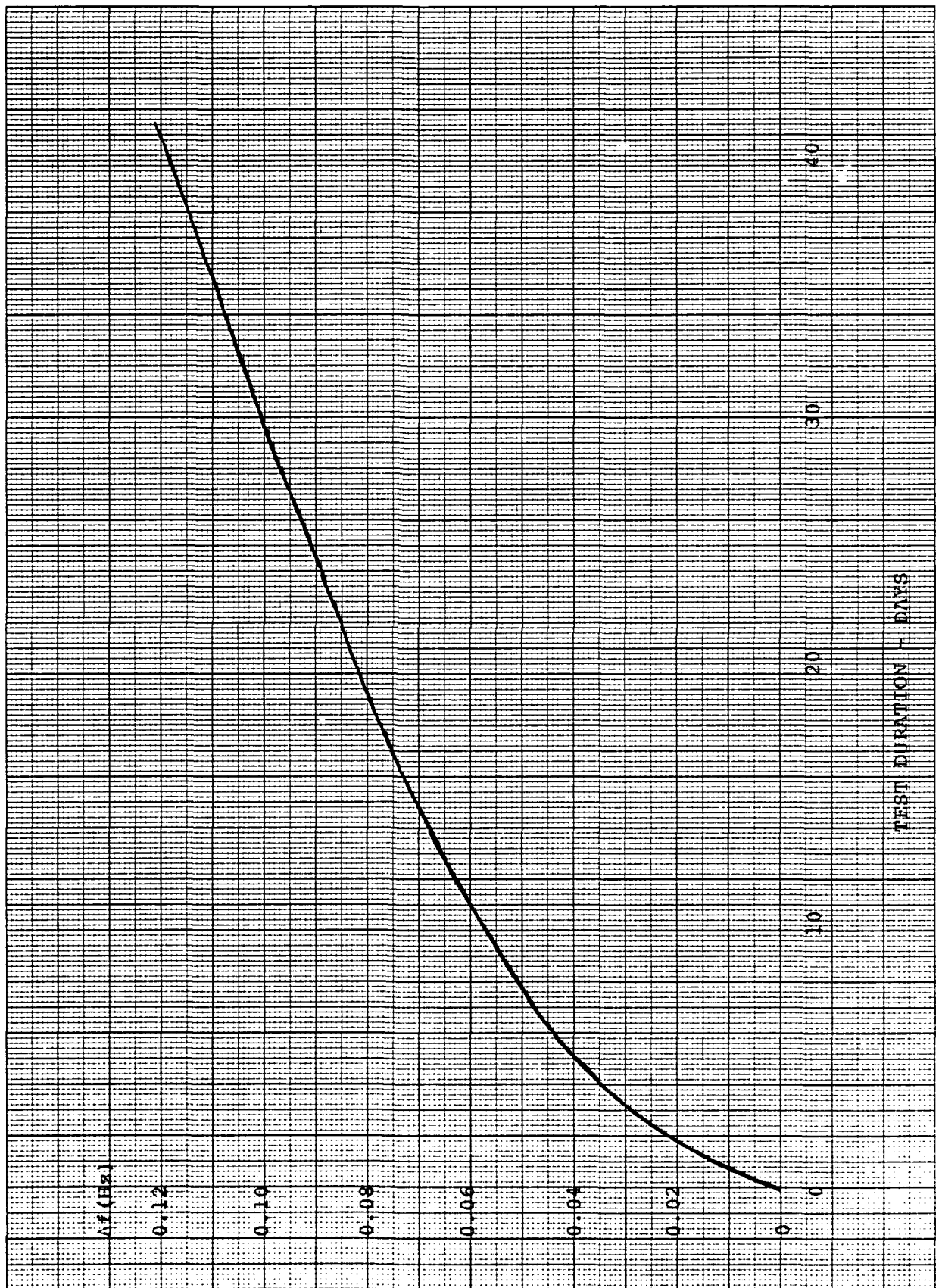


FIGURE 2-22 CRYSTAL CR 186 AGING WITH 110 PF IN SERIES

(This measurement is without the capacitor, and at 0.7 ma crystal current level). Further measurements will be necessary to obtain the distribution of crystal drift rates, and to characterize drift rates associated with other components (coils, varactors, etc.)

2.B MECHANICAL DESIGN

The mechanical design of the TMXO has progressed steadily in several areas since the adoption of the concept illustrated in Figure 2-23.

As a result of the investigations described in the following sections and, in some cases, as a result of more detailed information becoming available as the design progressed, the TMXO Cross Section shown in Figure 2-24 evolved and is the present conceptional approach at the end of this reporting period.

Since firm electronic circuit design had been delayed, as described in previous sections, and due to the very tight packaging anticipated, few hardware commitments were made due to the custom design and tooling required of the major components. Additionally, crystal package size inconsistencies between reported size and measured size prevented firm commitments since the entire Bendix design circuitry utilized the crystal package as a support structure which then was mounted inside the inner housing.

The most significant change from Figure 2-23 is the change of the inner container from glass to the same materials selected for the outer housing.

In arriving at the configuration shown in Figure 2-24, constant trade offs were required based on size, weight, risk, known techniques and many other factors. In some cases, a direction taken in one of the major categories, i.e., feed-throughs, sealing, when considered in the other categories was found to be less than desirable. As a result, as in any design, new directions were required when the overwhelming facts dictated the new direction to be taken.

(1) GETTER MATERIAL SELECTION. The ability to maintain a vacuum $< 1 \times 10^{-4}$ TORR for long periods of time with the maximum outgassing temperature during the evacuation of the outer housing being limited to 150°C led to the search for a suitable getter to be utilized in the TMXO. In vacuum tube practice, temperatures on the order of 600°C to 700°C are typically employed

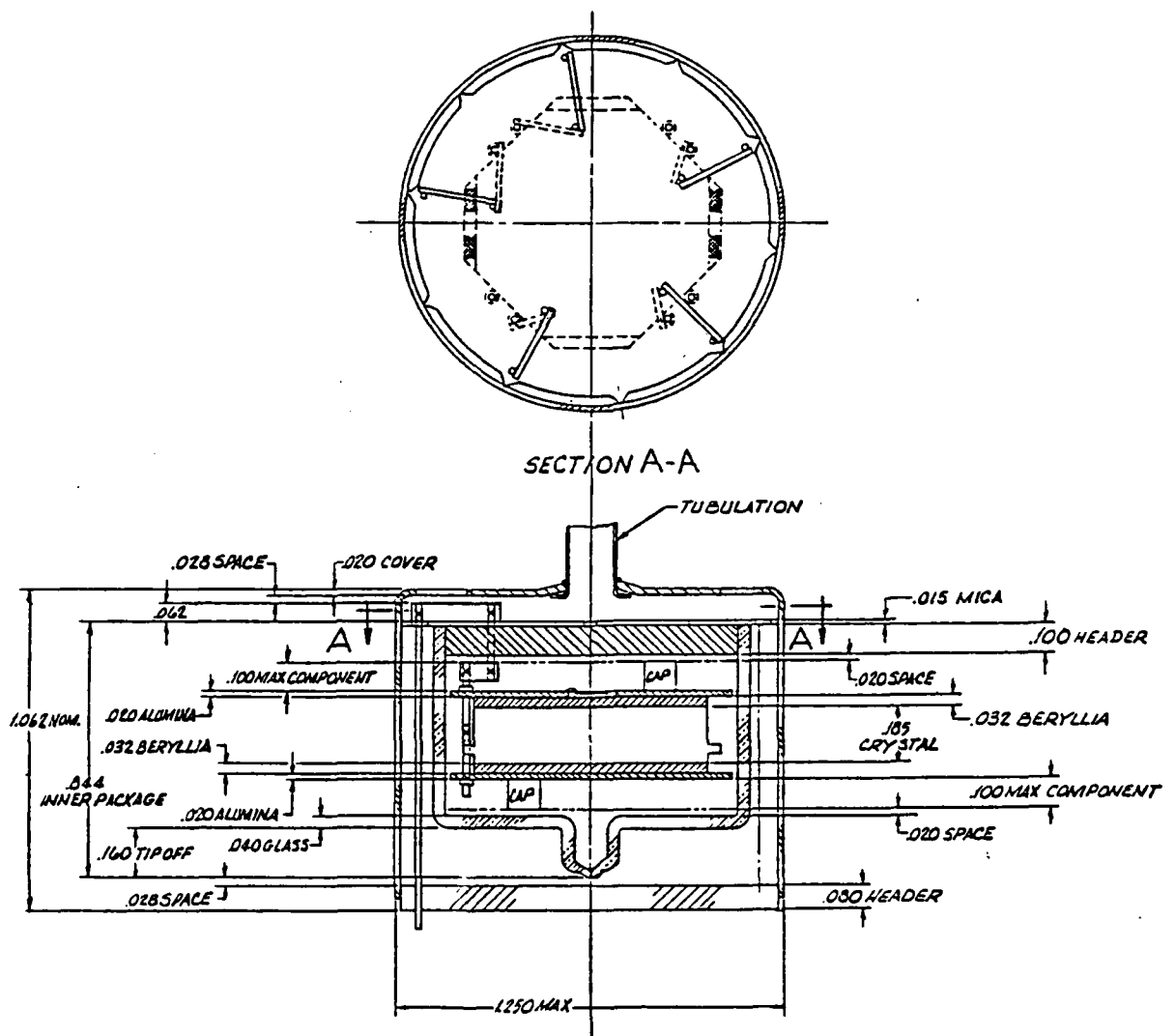


FIGURE 2-23

OVERALL CONCEPT



to assist in driving off the gasses in and on the components during evacuation. Additionally, getters are typically flashed to eliminate residual gasses and are active at high temperatures.

Approximately thirty five getters were considered with the promising candidates reduced down to the chart shown in Table 2-4.

Of these, the Zi-C has a distinct advantage in that it can be activated more than once. This would allow several opportunities to evaluate the pressure build up and the functioning of the TMXO after seal-off and getter activation. Samples of this type of getter have been received from SAES. Additionally, Ronson's Ceralloy 400 getter had been used in previous endeavors and proper activation of the Ceralloy 400 may produce the desirable characteristics.

Other getters were investigated but were found unsatisfactory for our purposes. These included the Tantalum and Zirconium getters, both of which had operating temperatures which far exceeded the maximum temperature of the TMXO. The Batalum getter with its prohibitive high degassing temperature was also unsatisfactory, as well as several others which were not continuous (Magnesium & Al-Mg).

Before further evaluation of the suitable getters resumes however, the gas load of the TMXO must be defined. Once the gas load is obtained, the data can be compared to the capacity and rates of the various getters for the different gasses and a selection of the TMXO getter will be made.

(2) FEED-THROUGH INVESTIGATION. Resolution of the type of material to be used for feed-through wires, and also for the header, required investigation of materials suitable for attachment to alumina and also to glass.

Material technical data sheets received from Carpenter Technology Division of Carpenter Steel were reviewed keeping in mind the following criteria:

TMXO GETTER SUMMARY

GETTER	TYPE	DEGASSING TEMP (°C)	GETTERING TEMP (°C)	FORMS AVAILABLE	MANUFACTURER (TRADE NAME)
BARIUM	FLASH @ 900°C	400-700	20-200	METAL CLAD, WIRE PELLETS	UNION CARBIDE (KEMET) SAES (ST14) ATOMERGIC
CETO	COATING	800-1200	200-300	POWDER, PASTE METAL CLAD	RONSON (CERAMLOY 400)
ZI-C	BULK	900-1000	20-400	COATING ON HEATER	SAES (ST171)
ZIAl	FLASH COATING	700-1000	<200	POWDER COATING	SAES (ST101)
Ba+Al+Th	FLASH @ 750°C	-	20-200	METAL CLAD, PELLETS	UNION CARBIDE (BATO)

TABLE 2-4 TMXO GETTER SUMMARY

- (a) Thermal expansion properties
- (b) Mechanical properties
- (c) Uses for which the material had previously been manufactured.
- (d) Forms of the material which were available such as sheets, wire, bar.
- (e) Availability of a particular material, i.e., from stock or long lead item.

Eight materials appeared as possible candidates, and these were reviewed to the criteria mentioned above. The materials were:

- Vacumet Kovar
- Glass Sealing 27
- Invar 36
- Glass Sealing 42
- Low Expansion 42
- Glass Sealing 42-6
- 46 Gas Free
- Glass Sealing 52

The review revealed that the foremost candidates were:

- Vacumet Kovar
- Low Expansion 42

Contact was made with Carpenter Technology Division metallurgists who confirmed that of the eight possibilities the two listed above should be selected. However, the discussion revealed that Low Expansion 42 in sheet form was only available in a mill run, and was not made in the diameter wire required, i.e., .010 to .020. Therefore, since both sheet form .06 to .100 and the wire sizes are required for the assembly, Vacumet Kovar which is made in both forms became the selection.

Vacumet Kovar is a vacuum melted low expansion alloy of nickel (29.00%), cobalt (17.00%) and iron (remainder) used for making hermetic seals with the harder Pyrex glasses and ceramic

materials. It has found wide use in power tubes, microwave tubes, transistors and diodes as well as integrated circuits. Its co-efficient of thermal expansion is $3.25 \times 10^{-6}/^{\circ}\text{F}$ at 212°F and $6.25 \times 10^{-6}/^{\circ}\text{F}$ at 1652°F . It is available in the forms required for this project.

Three possible brazing alloys for attaching metallized Alumina to Kovar are in order of preference:

- (a) Oxygen Free Copper, Flow Point 1060°C
- (b) 30% Gold, 70% Copper, Flow Point 1035°C
- (c) 72% Silver, 28% Copper, Flow Point 780°C

It should be noted that brazing alloys high in silver tend to attack the grain boundary of the Kovar. This may be alleviated by placing a layer of nickel on the Kovar, and to have the Kovar in the annealed condition prior to brazing. Brazing should be done in a protective atmosphere such as dry hydrogen, i.e., a strongly reducing atmosphere.

A hermetic seal facility was selected to provide the feed-throughs. This is Airpax Electronics, Hermetic Seal Division in Cambridge, Maryland. The feed-throughs techniques being considered are ceramic to metal. Ceramic is being considered, as opposed to glass, due to the superior strength realized with ceramic. Additionally, since the feed-throughs in the base are in the near vicinity of the weld joint, a brazed-in ceramic feed-through is considered less susceptible to damage during the welding operation. Airpax, although primarily dealing in glass to metal seals, was successfully producing simple and complex ceramic to metal seals. Further, their engineers considered the straight through design shown in Figure 2-24 feasible and demonstrated samples of similar designs. This approach was more in keeping with the overall packaging approach and less expensive in a production quantity.

Other ceramic to metal suppliers were contacted with various proposals being received. The requirements for space both inside and outside the packages was not considered to be in keeping with the extremely small size of the TMXO.

(3) SEALING INVESTIGATION. Early in the evolution of the new design concept, the use of a glass inner package, sealed by induction heating, was discarded for the following reasons.

1. Unknown reactions of miniature gold interconnecting wires on substrate in a high inductive field.
2. Potential problems in inducting heat into the Kovar sealing ring with plating on the glass housing.
3. Unknown reaction of active and passive components in the near vicinity of the induction field.
4. Impact on soldered joints in the inductive field.
5. Risk of contaminating the vacuum with plating on the glass.

It became apparent that the inner and outer package should be designed to employ the same materials and sealing techniques. The approaches considered included Seam Welding, Electron Beam Welding, Laser Welding and Ultra-sonic Welding. A welding service contractor was selected, and a joint design for Electron Beam welding of both packages was developed.

The contractor is EBTEC, in Agawam, Mass. They specialize in Electron Beam and Laser Welding, and in custom fabrication of welding systems for production use. Electron Beam welding was chosen due to the cleanliness during welding since it is performed in a vacuum. EBTEC now butt welds heart pacer cases and leak tests them to 1×10^{-8} ATM cc/sec. A butt weld is much more difficult to accomplish since there is no overlap of material. Samples were observed and the weld is very impressive. EBTEC was concerned with the ceramic feed-throughs in the outer base being in close proximity with the weld. The decision was made to proceed with an alternate outer header design. This design has the feed-through moved toward the center to avoid overheating during the weld cycle. This design will cause a different approach to be taken in the final assembly, since the wires will either have to bend or be spliced into the header feed-throughs to allow clearance of the electronics package.

Should problems arise in retaining seal integrity after welding the original design, the second header design will be welded to test the seal.

The plan was to fabricate outer bases at Bendix, contract Airpax to braze in the feed-throughs, leak test and transport to EBTEC to weld the packages. Leak testing will then be done on the completed units. Transportation of the parts to and from EBTEC will be accomplished in vacuum desiccator containers, since at this stage of the assembly, the parts to be Electron Beam welded will have been rigorously cleaned and vacuum baked to reduce outgassing.

Decision on the location of the ceramic feed-throughs will be based on this welding experiment.

(4) THERMAL ANALYSIS. Since it has been recognized that proper thermal design is critical to meeting many TMXO performance specifications, considerable effort has been directed toward development of a computer model to provide design guidance prior to model construction. For example use of the program should:

- a) Determine the temperature of nodes within the TMXO at the high ambient temperature (Steady State).
- b) Determine the temperature of the nodes at low ambient temperature (Steady State).
- c) Determine the change in crystal temperature as a result of noise in the thermal control circuit.
- d) Determine the optimum location for the control thermistor.
- e) Determine the stabilization time for warm-up from a cold start.
- f) Determine the impact of ambient temperature steps on the crystal.

This effort is following parallel paths. Bendix Research Labs has been tasked to model the TMXO and run the model to determine temperatures and stabilization times based on the present design. Options, such as wire diameter, gas pressures, (inner and outer enclosure), heat input and emissivities are built into the model. The program is a standard program used at the Research Labs.

As a parallel effort, a computer services company was contacted to determine the availability of thermal programs that could be modeled by Bendix Communications Division. Control Data Corporation supplied BCD with the instruction book for the MITAS II "Interactive Thermal Analysis Program". An Abstract of the program is shown below.

ABSTRACT

The Martin Marietta Interactive Thermal Analysis System, MITAS-II-NOS-FTN Version, is a general software system designed to solve, primarily, lumped parameter, i.e., resistor-capacitor(R-C), network representations of thermal systems. With due attention to thermal peculiarities of library routines and appropriate units, MITAS-II is fully capable of solving lumped-parameter representations of any physical problem described by diffusion-type equations using finite-difference, thermal analogue methods. In addition, MITAS-II can be used as a general purpose program with utilization of its array and constant capability along with library or user subroutines by simply ignoring the network definition inputs.

MITAS-II is an extensively updated version of MITAS-I and CINDA-3G thermal analyzer programs. It can be used to solve small or large problems with "floating" core memory requirements and significant user input logic capabilities. Maximum network size is 4,000 nodal areas, 16,000 unique conductors and 1,024 input arrays. MITAS-II also has extensive edit and restart capabilities for extended or parametric case runs.

This MITAS-II version has been converted to Fortran Extended and operates using the NOS operating system.

The TMXO was divided into approximately 400 nodes to allow temperatures time analysis by the MITAS-II program.

Several attempts were made to reach a steady state solution on the nodal analysis with incomplete results. Discussions with Martin Marietta (the original developer of the program), the extreme degree of accuracy required, a large number of iterations would be required to converge on a solution. A restart capability was built into the program to allow a continuation toward a convergence rather than returning to the original node start temperature. Several restarts were attempted to demonstrate the correctness of this procedure.

A run was made at an ambient of 75°C and a nodal start temperature of 84°C, with heat inputs distributed on the two substrates to represent the idle power of .0349 watts. After 3000 iterations the system balance was diverging instead of converging toward the limit. Figure 2-26 shows a plot of results based on outputs every 200 iterations. Legends are:

- EBALSC - Calculated System Balance
- EBALSA - Desired System Balance
- EBALNC - Calculated Nodal Balance
- EBALNA - Desired Nodal Balance
- DRLXCC - Calculated ΔT Change
- DRLXCA - Desired ΔT Change
- EXTLIM - Maximum Allowable ΔT .

The program, for efficiency reasons, is required to satisfy the following in order:

- a. $DRLXCC \leq DRLXCA$
- b. $EBALSC \leq EBALSA$
- c. $EBALNC \leq EBALNA$

The first criteria (ΔT Changes) was met at 601 iterations. However, the system balance (EBALSC) was diverging and at the end of 3000 iterations was 45 times the desired criteria and the nodal balance (EBALNC) was 56 times the desired criteria. When item c above is met, the problem is considered to have reached a steady state solution. The limits chosen (EXTLIM) were based on conversations with the Martin Marietta Programmers, since this criteria must be carefully defined to prevent oscillations and allow convergence.

MODEL TMXO THERMAL MODEL II

DATE 9/6/79

K&E SEMI-LOGARITHMIC 46 6463
7 CYCLES X 60 DIVISIONS
MADE IN U.S.A.
KEUFFEL & ESSER CO.

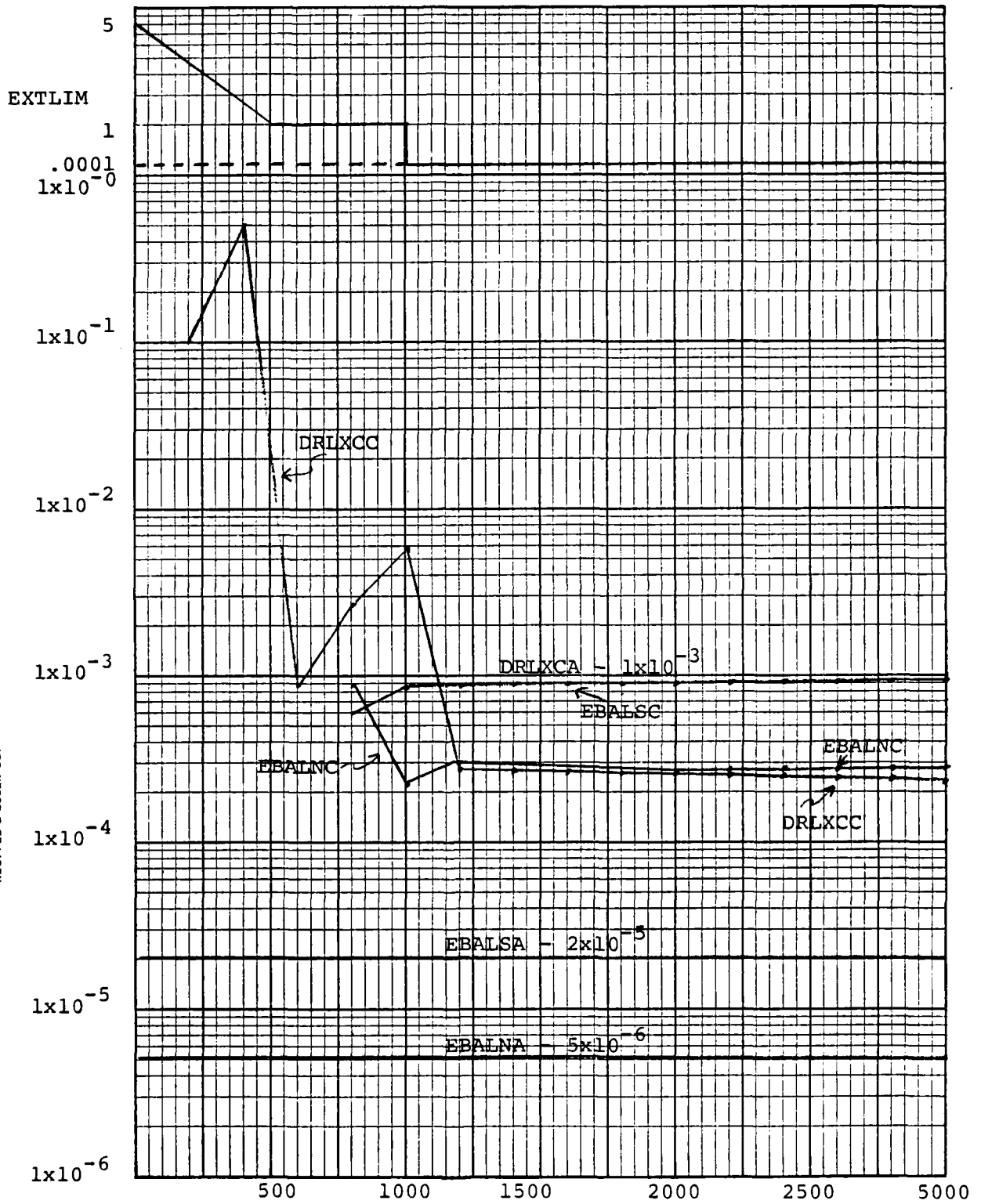


FIGURE 2-25 NO. OF ITERATIONS

The results shown were discouraging, since it was impossible to predict if and when the system balance (EBALSC) would change slope and converge.

The original plan was to obtain a solution at the high ambient with the assumption that computer run time would be minimum and that the model would be proven, since some of the expected temperatures were known based on previous calculations.

To date, several thousand dollars have been expended in the computer without obtaining a solution at the assumed least cost run point. Approximately 30% of this was expended in run time and the other costs were in loading, editing and changing.

Martin Marietta computer services was contacted and agreed to load the model into their computer and duplicate the 3000 iteration run previously run at no cost. There were several advantages to this approach:

- a. Computer run time was less costly.
- b. Martin could lend technical assistance toward efficiently converging.
- c. Martin could study the TMXO model.

Control data corporation agreed to run the TMXO Model (at no cost to Bendix) until it converged or until it was determined that the program was incapable of dealing with the low powers and extremely small temperature changes desired. To date, with the ambient set to -54°C and the power output set to .25 watts, 24,000 iterations have been attempted without a convergence. This effort has been terminated.

The Bendix Research Laboratories thermal program is now up and running on the Bendix Communications remote terminal and efforts have continued, on a small nodal basis, to evaluate the design. The purpose of this effort is to evaluate the impact of mica spacers on the thermal properties of the system. Presently, a lumped 5 node, 12 conductor network is being analyzed without air conduction being considered in either container.

The results to date confirm earlier calculations that the system cannot be designed for a worst case condition and meet the requirements of the specification if the crystal turn point is at $89^{\circ}\text{C} \pm 5^{\circ}\text{C}$.

If that is the case, using a simple linear system on a worst case basis, the following results are evident:

<u>At 54°C</u>		<u>At $+75^{\circ}\text{C}$</u>	
Crystal Temp.	= +94	Crystal Temp.	= +84
Amb. Temp.	= <u>-54</u>	Amb. Temp.	= <u>+75</u>
$\Delta T = 148^{\circ}\text{C}$		$\Delta T = 9^{\circ}\text{C}$	
$\frac{\Delta T}{\text{Power}} = \frac{148}{.25} = \frac{592^{\circ}\text{C}}{\text{Watt}}$		$\frac{\Delta T}{\text{Power}} = \frac{9}{.030} = \frac{300^{\circ}\text{C}}{\text{Watt}}$	

Obviously, when considered on a linear basis, the two end point conditions are not compatible since they should be of equal resistance. Radiation losses, being a function of the temperature differences to the fourth power, tend to improve the situation but fail to completely solve the problem.

These problems and initial calculations were based on the system originally proposed. The new configuration, after repeated attempts to optimize wire diameters, radiation losses and conductive losses through the mica spacer, still shows similar results. Therefore, Bendix assumes for future TMXO fabrications, that the crystal turn temperature will be revised upwards based on the results obtained during this phase.

Turn temperature on crystals delivered to date range from 78°C to 91°C . Crystal with higher turn points will result in a higher power requirement at the -54°C ambient, but the change is necessary since the electronics power is minimum for the requirements and must be dissipated at the high ambient to maintain crystal temperature and thus frequency control. Two additional investigations have been completed in this period: "The Selection of the TMXO Crystal Package Heat Spreader", and "A Comparison of Radiation and Conduction Heat Losses Around the TMXO Oscillator Package:", which was generated in response to an

ERADCOM request to consider the use of an insulator in conjunction with the vacuum in the TMXO. These results are described in the following Tech Notes.

TECH. NOTE 1

DATE 13 April, 1979

TACTICAL MINIATURE CRYSTAL OSCILLATOR
(TMXO)

SELECTION OF TMXO CRYSTAL
PACKAGE HEAT SPREADER

Prepared for
U. S. ARMY
ELECTRONIC RESEARCH & DEVELOPMENT COMMAND
FT. MONMOUTH, N.J. 07703

Under
Contract DAAB07-78-C-2990



The Bendix Corporation
Communications Division
East Joppa Road
Baltimore, Maryland 21204

SELECTION OF TMXO CRYSTAL PACKAGE HEAT SPREADER

ABSTRACT: A thermal analysis has been performed to determine materials to be used around the TMXO crystal package. A computer program has been written to aid in the design process. Preliminary results show that there are several materials available which meet the design criteria.

Introduction

The alumina crystal package must be maintained at a near uniform temperature in order to avoid a temperature differential across the crystal gas space. Meager temperature variations across the crystal will impact upon the crystal frequency. Presumably, the crystal heating source (transistor) will have a small surface area interfacing with the top plate of the crystal package heat spreader. The function of the heat spreader will be to disseminate heat supplied by the heating source around the alumina package, so that the crystal is submerged in a thermally stable environment.

Heat Conduction Around Crystal Package

In figure 1(a) is shown a diagram of the crystal package. The crystal is surrounded by nitrogen and is suspended by wires to the alumina package which is covered on top and bottom by the heat spreader. The heating source is assumed to be a square transistor of width W .

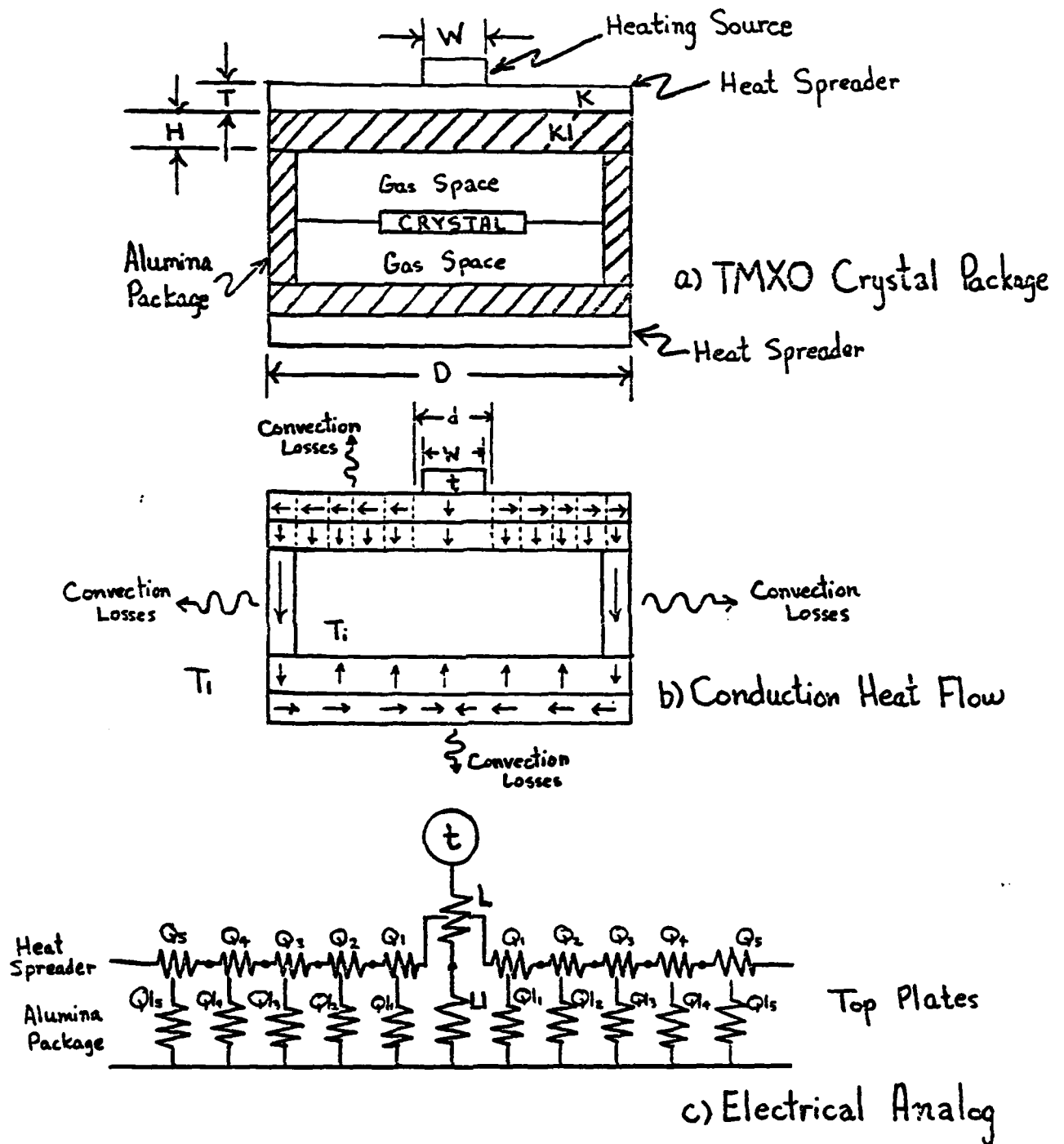


Figure 1. Diagram of Conduction Heat Transfer in TMXO Crystal Package

Design requirements are such that the heat spreader be composed of a high conducting material relative to the alumina. A schematic of the desired conduction heat flow is shown in figure 1(b). Conduction heat flow through the heat spreader is required to be rapid and of low thermal resistance so that it spreads radially around the alumina top plate much faster than the alumina conducts across the crystal gas space. Assuming heat is conducted through the crystal package sides as shown in the diagram, the heat source effectively balances convection losses in the space surrounding the crystal package.

If a cross section of the upper plate is divided into equal segments the heat conduction through the package can be observed. An electrical analog of the heat conduction along the top plates for five equal divisions is shown in figure 1(c). Heat dissipated through the heat spreader at L is distributed through the alumina top plate L1 and radially along the heat spreader elements Q. Heat transfer also occurs from the heat spreader through the alumina column elements Q1. Design requirements are such that the heating source of width W, and the heat spreader of thermal conductivity K and thickness T be specified.

The thermal resistance equations are:

For the heat spreader;

$$L = \frac{T}{K \cdot A1} \quad \left(\frac{^{\circ}\text{C}}{\text{watt}} \right)$$

$$Q = \frac{\ln \left(\frac{R2}{R1} \right)}{2\pi KT} \quad \left(\frac{^{\circ}\text{C}}{\text{watt}} \right)$$

For the alumina package;

$$L1 = \frac{H}{K1 \cdot A1} \quad \left(\frac{^{\circ}\text{C}}{\text{watt}} \right)$$

$$Q1 = \frac{H}{K1 \cdot A2} \quad \left(\frac{^{\circ}\text{C}}{\text{watt}} \right)$$

Computer Simulation of Heat Loss in Crystal Package

A computer program has been written which simulates heat flow around the upper plates of the crystal package. The program calculates the thermal resistance of the heat spreader and the alumina package. Design parameters to be input into the program are the heat spreader thermal conductivity $K \left(\frac{\text{watts}}{\text{cm} \cdot ^{\circ}\text{C}} \right)$ and thickness $T(\text{in})$, and the heater width $W(\text{in})$. Cylindrical heat flow is assumed from the heating source through the top plates such that the radius of the cylinder whose cross sectional area is equal to the surface area of the square heating source is determined.

Column losses L and $L1$ are then calculated across the heat spreader and the alumina plate. The radial resistance of the heat spreader Q and the resulting column losses across the alumina plate $Q1$ are then determined for the five divisions shown in figure 1. A listing of the computer program along with a sample of output data is shown in figure 2.

Selection of Heat Spreader

After the thermal resistances in the top plates have been determined for several values of W , K and T the following functional relations are available:

```

10 DATA 1.0
20 B=0
30 B=0.75
40 K=0.5+2.5*I/2
50 WIDE CONDUCTIVITY(WATTS/CM C)"
60 INPUT K
70 DIM HEATER SIZE(IN)"
80 INPUT W
90 DIM BEO THICKNESS(IN)"
100 INPUT T
110 T=T*2.54
120 R1=0.183
130 R1=W*2
140 R1=VR1+4-R1*10.5
150 R1=R1/2+0.34
160 R1=R1-R1*2
170 L=T/(K+R1)
180 H=0.935*2.54
190 L1=H/(K1+R1)
195 S=0.1731610
200 PRINT TAB4;"R1(IN)";TAB14;"R1(IN*2)";TAB24;"R2(IN)";TAB34;"R2(IN*2)";
205 PRINT TAB44;"Q(C/WATT)";TAB54;"Q1(C/WATT)";
210 FOR R2=S+S/2 TO S*5.5 STEP S
215 R1=R1+R1*2
220 R2=R1+R2*2-R1+R1*2
225 Q=LOG(R2/R1)/(2*PI*K*T)
230 Q1=H/(K1+R2)
235 R1=R1/2.54*2
240 R2=R2/2.54*2
245 WRITE (15,295)R1/2.54,R1,R2/2.54,R2,Q,Q1
250 FORMAT (F10.4)
260 R1=R2
270 NEXT R2
280 PRINT "SPREADER COND(WATTS/CM C)"K
290 PRINT "HEATER SIDE DIM(IN)"W
300 PRINT "BEO THICKNESS(IN)";T/2.54
310 PRINT "TAL COND(WATTS/CM C)"K1
320 PRINT "COLUMN LOSS L(C/WATT)"L
330 PRINT "COLUMN LOSS L1(C/WATT)"L1
340 STOP

```

```

1. RUN
CONDUCTIVITY(WATTS/CM C)0.2.34
HEATER SIDE DIM(IN)0.1
BEO THICKNESS(IN)0.01

```

R1(IN)	R1(IN*2)	R2(IN)	R2(IN*2)	Q(C/WATT)	Q1(C/WATT)
0.183	0.366	0.183	0.366	1.5928	3.2063
0.366	0.732	0.732	1.464	1.3679	1.2547
0.732	1.464	1.464	2.928	0.9910	0.9354
1.464	2.928	2.928	5.856	0.6730	0.6273
2.928	5.856	5.856	11.712	0.5373	0.5019

```

SPREADER COND(WATTS/CM C) 2.34
HEATER SIDE DIM(IN) 0.1
BEO THICKNESS(IN) 0.01
TAL COND(WATTS/CM C) 0.100
COLUMN LOSS L(C/WATT) 0.163246200
COLUMN LOSS L1(C/WATT) 0.129535930

```

Figure 2. Computer Simulation of Heat Loss in Crystal Package.

For the heat spreader:

$$\left. \begin{array}{l} Q = f(W, K, T) \\ L = f(W, K, T) \end{array} \right\} \text{Minimize } (L+Q)$$

The alumina is chosen for a known K_l and thickness H :

$$Q_l = f(W)$$

$$L_l = f(W)$$

Following several runs of the computer program the curves shown in figures 3 and 4 were constructed for the two materials being investigated; beryllia ($K = 2.34 \frac{\text{watts}}{\text{cm}^\circ\text{C}}$) and copper ($K = 4.05 \frac{\text{watts}}{\text{cm}^\circ\text{C}}$). The overall resistance is obviously lower for the copper because of its higher conductivity. As seen in the figures the thermal resistances decrease as the heater width increases. The maximum value of W is limited by the size of the transistor available to meet the design specifications.

Although the column loss L increases as t increases the radial resistance decreases faster as t increases, such that the total resistance Q also decreases with t . In comparing beryllia to copper, it is observed that a sample of beryllia almost twice as thick as copper is required to achieve a comparably low resistance.

However, the final design consideration is based on the mass density of the material to be used. In comparing Beryllia ($\rho = 3.88 \text{ g/cc}$) to copper ($\rho = 8.94 \text{ g/cc}$) a given sample of copper is 3 times more dense than beryllia. Thus for a given cross section of material, a mass of Beryllia 1/3 less than copper is required to achieve comparable resistivity.

Figure 3. Graph of Thermal Resistances vs. Heater Width for beryllia heat spreader ($k=2.34 \frac{\text{watts}}{\text{cm}^2\text{-}^\circ\text{C}}$).

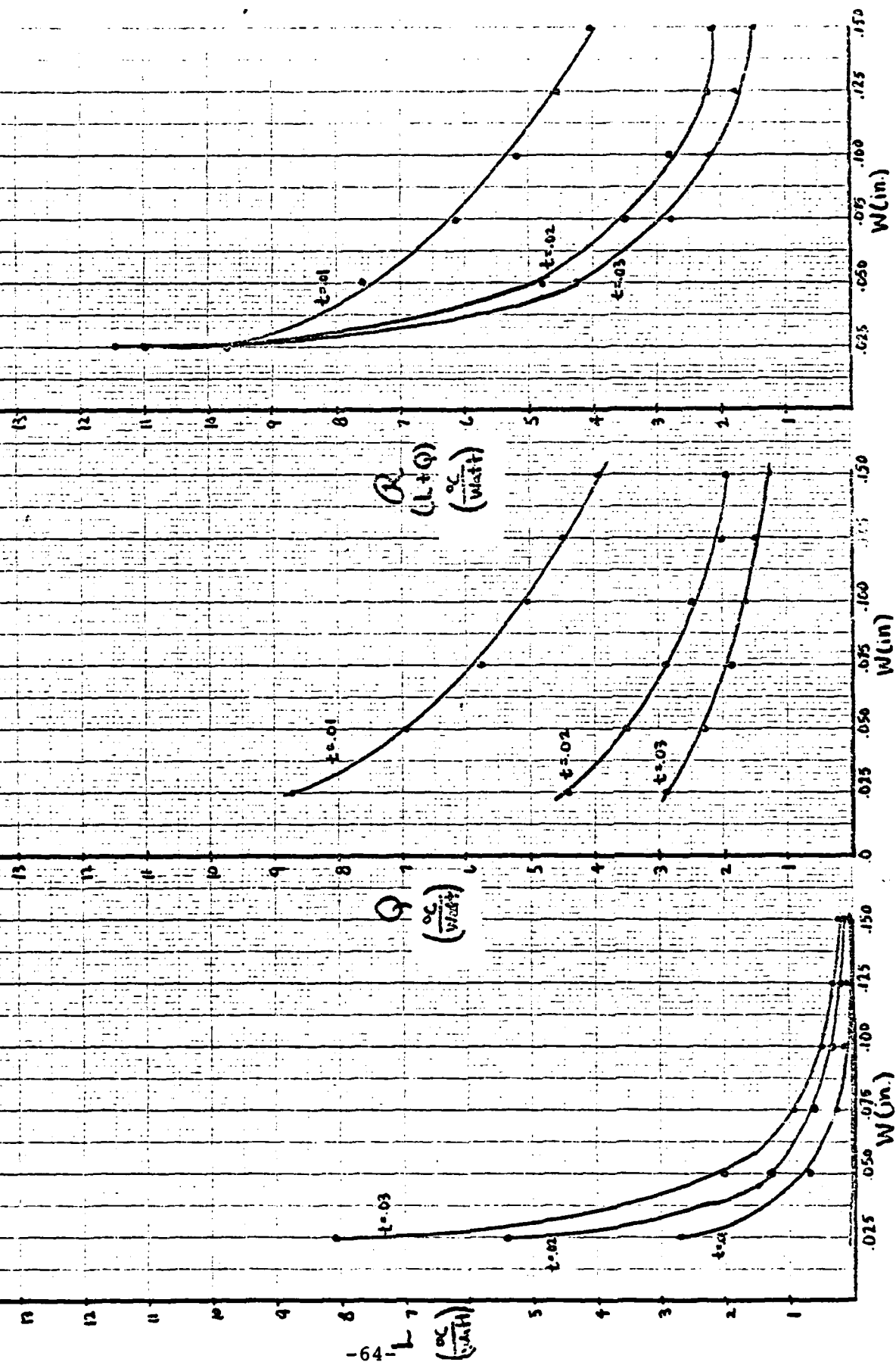
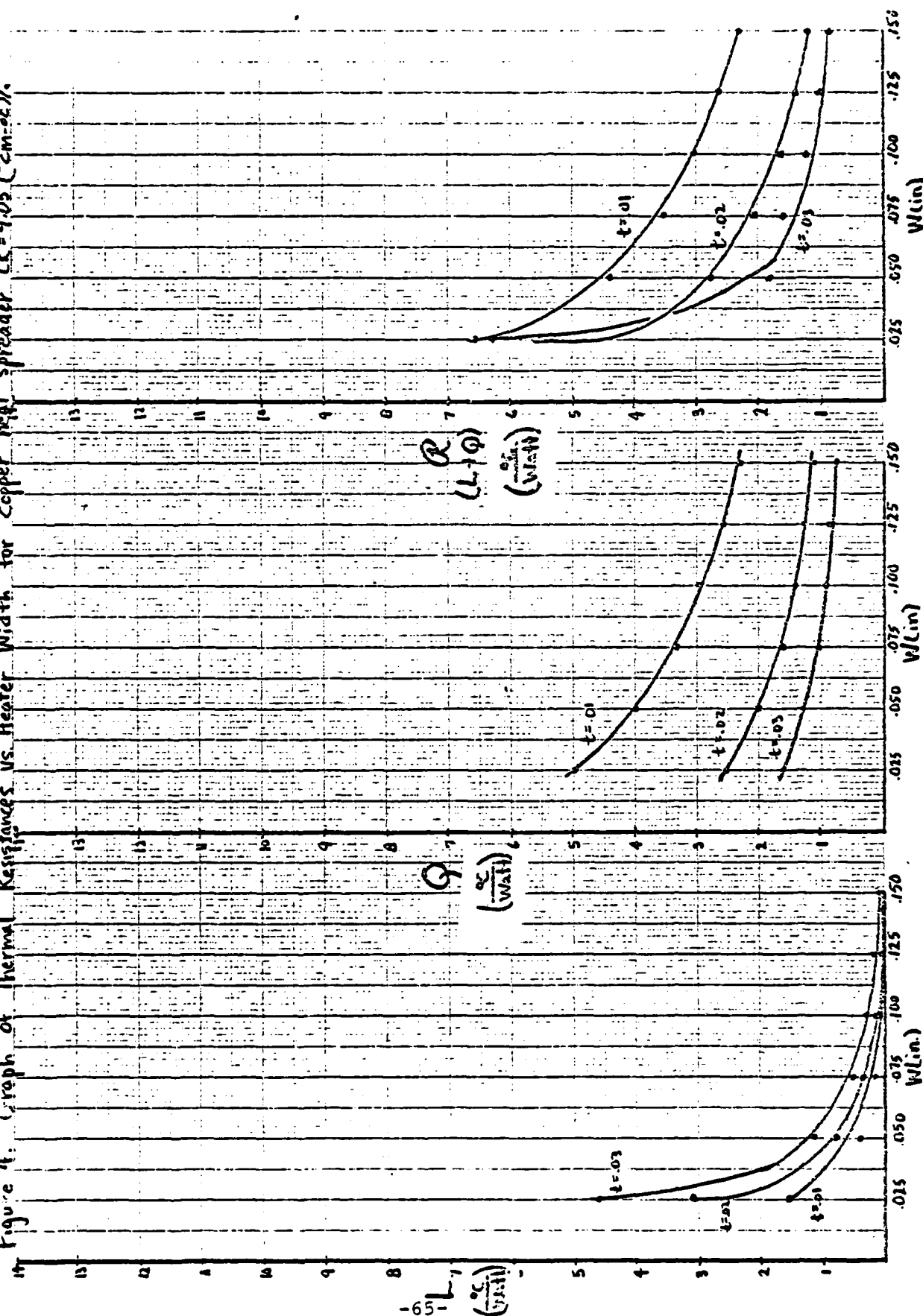


Figure 4: Graph of Thermal Resistances vs. Heater Width for copper heat spreader ($k = 4.05 \frac{\text{Watt}}{\text{cm} \cdot ^\circ\text{C}}$).



Conclusions

Results show that for a given heating source of width W , several materials of thermal conductivity K , thickness T , and density ρ are available which meet the performance criteria. A brief comparison of beryllia and copper shows that beryllia is a more suitable material for the heat spreader than copper.

TECH. NOTE 2

DATE 20 April, 1979

TACTICAL MINIATURE CRYSTAL OSCILLATOR
(TMXO)

COMPARISON OF RADIATION AND
CONDUCTION HEAT LOSSES AROUND
THE TMXO OSCILLATOR PACKAGE

Prepared for

U. S. ARMY

ELECTRONIC RESEARCH & DEVELOPMENT COMMAND

FT. MONMOUTH, N.J. 07703

Under

Contract DAAB07-78-C-2990



The Bendix Corporation
Communications Division
East Joppa Road
Baltimore, Maryland 21204

COMPARISON OF RADIATION AND CONDUCTION HEAT LOSSES AROUND THE TMXO OSCILLATOR PACKAGE

ABSTRACT: Heat transfer losses around the TMXO Oscillator Package have been calculated. Comparisons have been made between radiation heat losses in an evacuated space and conduction losses in the same space filled with insulating material. Preliminary results show that for conduction losses to be comparable, the thermal conductivity of the insulating material must be extremely low.

Introduction

The heat losses in the area between the TMXO oscillator package and the outer package are critical in conforming to overall design specifications. Inserting the oscillator package in a vacuumed enclosure would eliminate all heat losses other than radiation losses. Before investigating the complications which may develop inside the package under vacuum conditions, the conduction heat losses incurred, if the air space is filled with insulation material, will be determined. If the conduction approach proves to be feasible, an insulation material which meets the performance criteria would then have to be identified.

Radiation Losses

The radiation heat losses from the oscillator package are primarily dependent on the total outer surface area (A_s) of the oscillator package, the resultant emissivity of the two reflecting surfaces (ϵ), and the temperature difference

between the two surfaces. This is expressed as

$$Q_r = .293 \times 10^{-8} \cdot \sigma \epsilon A_s (T_i^4 - T_o^4) \text{ watts} \quad (1)$$

where σ is the Stefan-Boltzmann constant. The total outer surface area of the oscillator package can be calculated using the dimensions shown in figure 1(b), where the additional area attributable to the tipoff portion of the package is considered negligible.

The radiation heat losses can then be expressed as a function of the emissivity (ϵ), assuming that the oscillator package is at a uniform temperature $T_i=94^\circ\text{C}$, and that the outer package temperature T_o is variable.

$$Q_r = \begin{cases} 2.230 \cdot \epsilon & \text{if } T_o = -55^\circ\text{C} \\ 0.487 \cdot \epsilon & \text{if } T_o = 75^\circ\text{C} \end{cases} \quad (2)$$

Conduction Losses

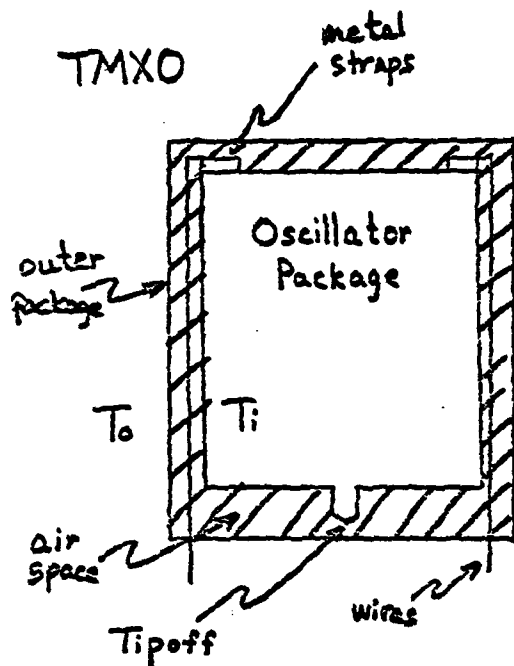
The heat losses through the insulating material can be calculated by summing up conduction losses for the four regions shown in figure 1(b). The heat loss from the metal straps at the top of the package are assumed negligible. The conduction heat transfer equation used is

$$Q_c = \frac{2\pi k L_1 \Delta T}{\ln(r_o/r_i)} + \frac{\pi k r_2^2 \Delta T}{L_2} + \frac{\pi k (r_3^2 - r_4^2) \Delta T}{L_3} + \frac{\pi k r_4^2 \Delta T}{L_4} \quad (3)$$

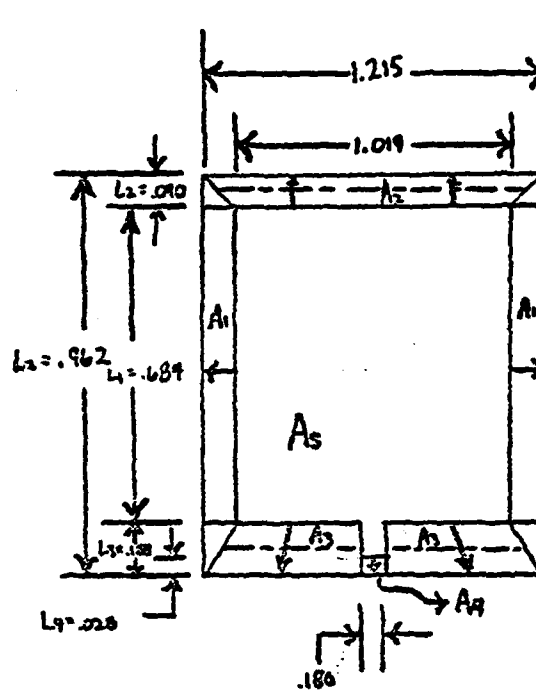
The conduction heat losses are then expressed as a function of the thermal conductivity (k) of the insulation material, assuming the same ambient temperature conditions as in equ. (2).

$$Q_c = \begin{cases} 270.984k & \text{if } T_o = -55^\circ\text{C} \\ 34.550k & \text{if } T_o = 75^\circ\text{C} \end{cases} \quad (4)$$

NOT TO SCALE



(a)



(b)

$$A_5 = 2\pi r_0 L_1 + 2(\pi r_0^2)$$

$$A_1(r) = 2\pi r L_1$$

$$A_2 = \pi r_2^2$$

$$A_3 = \pi(r_3^2 - r_4^2)$$

$$A_4 = \pi r_4^2$$

$$r_0 = \frac{d_0}{2} = .059"$$

$$r_2 = r_3 = \frac{1.215 + 1.019}{2 \cdot 2} = .5585"$$

$$r_4 = .09"$$

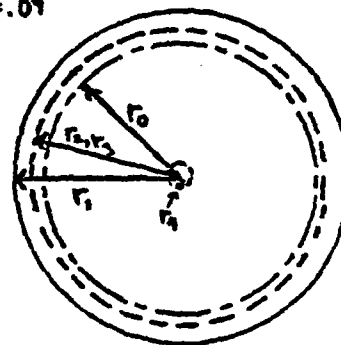


Figure 1. Schematic of TMXO package

Comparison of Radiation and Conduction Losses

A comparison can be made between the radiation and conduction losses by equating eqns. (2) and (4). The comparison will be based on realistic values attainable for ϵ and k . By assuming that the heat transfer loss is the same in both cases ($Q_c = Q_r$) the results are

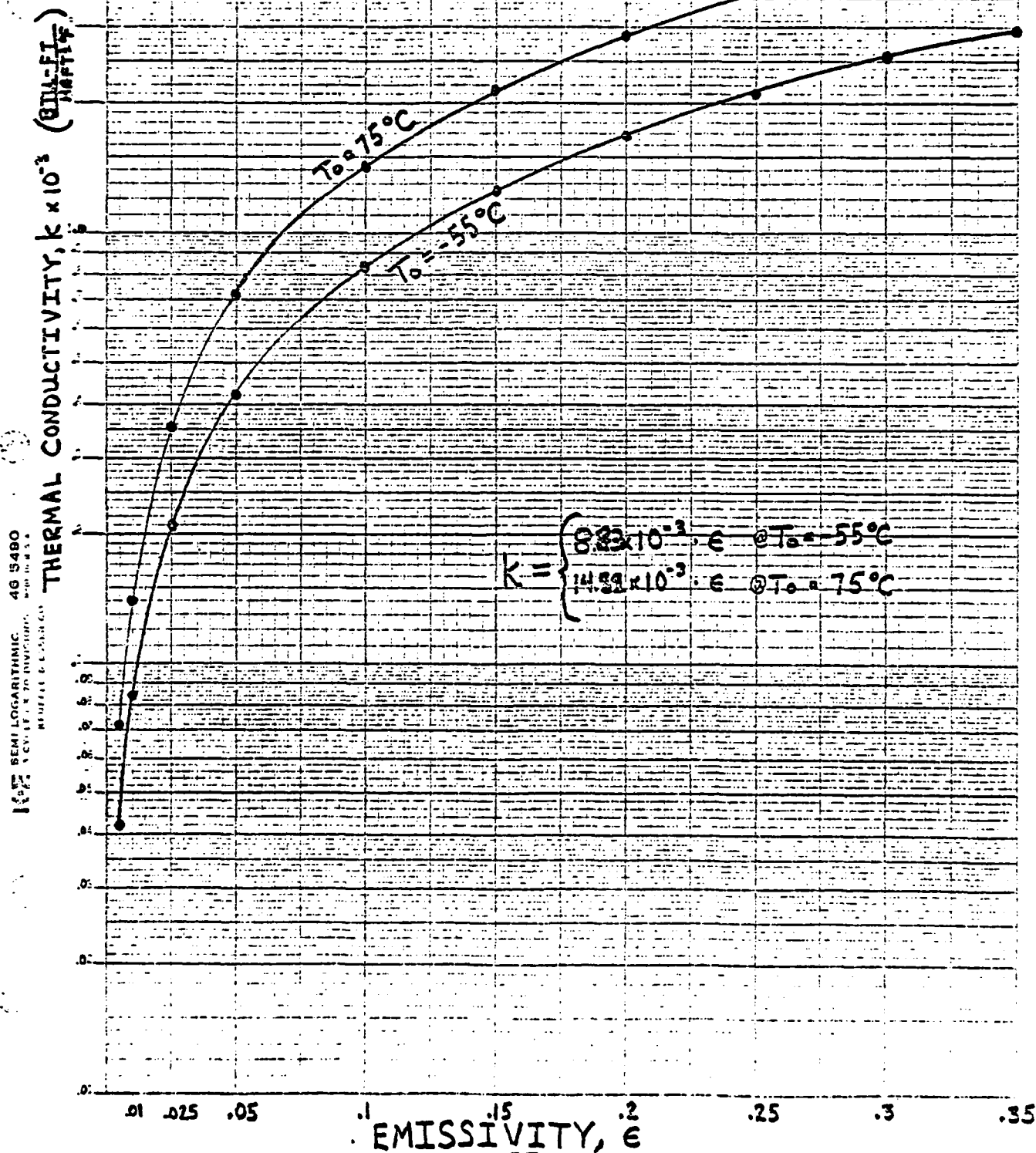
$$k = \begin{cases} 8.23 \times 10^{-3} \cdot \epsilon & \text{if } T_o = -55^\circ\text{C} \\ 14.11 \times 10^{-3} \cdot \epsilon & \text{if } T_o = 75^\circ\text{C} \end{cases} \quad (5)$$

As shown on the graph in figure 2, the value of k required to maintain conduction losses on a comparable scale with radiation losses is extremely low. In this analysis, a typical ϵ value of .05 would require a k value of $.00041 \frac{\text{BTU-FT}}{\text{HR-FT}^2-\text{°F}}$. An investigation of the k value data for Min-K TE series high temperature insulation (in vacuum) shows that the lowest k value of around $.008 \frac{\text{Btu-FT}}{\text{HR-FT}^2-\text{°F}}$ would not be sufficient. It is unlikely that any insulation material is available that could meet this performance criteria.

Conclusions

Preliminary results show that the insulation material required for comparable conduction heat transfer in this analysis requires a near zero k value. Filling the air space around the oscillator package with insulation material would result in more heat loss than through radiation.

FIGURE 2. GRAPH OF EMISSIVITY VS. THERMAL CONDUCTIVITY
FOR COMPARABLE RADIATION AND CONDUCTION
HEAT LOSS



$$k = \begin{cases} 8.33 \times 10^{-3} \cdot \epsilon & @ T_0 = -55^\circ\text{C} \\ 14.59 \times 10^{-3} \cdot \epsilon & @ T_0 = 75^\circ\text{C} \end{cases}$$

3. CONCLUSIONS

As a result of the work performed during this period, we conclude:

1. Regarding the fundamental 5.115 MHz ceramic flat pack crystals evaluated so far;
 - a) Two of the crystals have demonstrated acceptable short term stability; twenty-five fail to meet the requirement.
 - b) Phase perturbation measurements indicate the source of the measured frequency perturbations to be the crystal itself.
 - c) Two of the crystals have demonstrated excellent re-trace performance.
 - d) The long term stability has been evaluated on the two crystals having acceptable short term stability; the measured rates of 1×10^{-10} /day and 2.5×10^{-10} /day are in excess of the 2×10^{-10} /week requirement.
 - e) The aging rate of the crystals does not depend on excitation over the range of 50 amps to 700 amps.
2. Of the sixteen 10 MHz third overtone ceramic flat pack crystals on hand, almost half have turn temperatures below 84°C. Short term stability has not yet been evaluated.
3. The measured contribution of the porcelain dielectric chip capacitors to the aging rate of the fundamental crystal oscillator is in excess of the oscillator specification limit.
4. Materials and processes have been chosen for the mechanical design.
5. Detailed computer modeling of the TMXO thermal response to the accuracy necessary for design requirements is impractical.
6. In order to maintain frequency stability at ambient temperatures up to +75°C, the crystal turn temperature must be higher than +89°C.

4. FUTURE PLANS

For the next six month period, effort will be directed toward the following accomplishments:

- 1) Completion of circuit design and substrate layout
- 2) Continuation of Crystal and Component Evaluation
- 3) Materials Selection and Sealing Techniques Evaluation
- 4) Development of Assembly Processing
- 5) Construction of Assembly and Test Fixtures
- 6) Construction and Evaluation of Prototype Units.

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